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## THESIS

PARAMETER PLANE DESIGN OF ELECTRICAL  
FILTERS CONTAINING NONLINEAR ELEMENTS

by

Roger Alan Nichols

December 1969

Thesis  
N4862

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Parameter Plane Design of Electrical  
Filters Containing Nonlinear Elements

by

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Submitted in partial fulfillment of the  
requirements for the degree of

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Michale, R.

~~Low Pass Filter~~

# ABSTRACT

A parameter-plane method, based upon a quasi-frozen assumption, for the design of electrical filters containing slowly varying nonlinear elements is presented together with examples of its application to the lowpass, highpass, bandpass and band-reject filter types. The nonlinear magnitude and frequency characteristics are presented in the form of parameter-plane graphs which allow value judgements to be made concerning the choice of nonlinear elements used in the filter design. The computer programs used to generate the graphs are also included.

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## I. INTRODUCTION

A filter is a frequency-sensitive unit which discriminates between desired and undesired frequencies. Ideally the filter would have a unity-gain passband and a zero-gain stopband with no transition region between the bands. Also, its phase shift would be linear within the passband. Such filters do not exist today. The ideal filter is the optimum case and serves as a standard of comparison for all other filters. Filter design usually stresses either the magnitude response or the phase response depending on the intended use of the filter.

Filters may be grouped into four distinct types based on their frequency discrimination: lowpass, highpass, bandpass, and band-reject. While classical design used passive, lumped, linear elements and image-parameter methods to realize these filter types, modern design uses the polynomial method of network synthesis and considers all types of elements in both their active and passive forms. The addition of nonlinear elements in these filters allows a closer approach to the ideal response than possible if the elements were linear. At the same time however, the design problem becomes more complicated.

A parameter-plane method for the design of filter circuits is presented in this thesis. The method provides a relatively simple, easy-to-use way of incorporating

nonlinear elements into the design of electrical filter circuits.

## II. THE PARAMETER PLANE METHOD

The mathematical analysis of a linear dynamic system usually evolves into the evaluation of the roots of a polynomial formed from the differential equation description of the system. The root locations of this characteristic equation are then interpreted with respect to the system response characteristics. Any change in any circuit parameter value, however, changes the root locations. Some changes will improve the circuit response while others will degrade it.

Mitrovic, Thaler, Siljak and others developed analysis methods which consider such parameter value variations [1]. The original method of Mitrovic was rather limited since only the last two coefficients of the characteristic equation were allowed to vary. Lines of constant damping ratio ( $\zeta$ ) were mapped from the s-plane into the plane of the variable coefficients using the characteristic equation as the mapping function. These transformed curves were then used to determine the variable coefficient values required to place the characteristic equation roots at desired locations.

Generalization and extension of Mitrovic's coefficient plane by Siljak and Hollister [2] led to the concept of the  $\alpha, \beta$  parameter plane. This method considers the variable coefficients of the characteristic equation as nonlinear functions of two system parameters,  $\alpha$  and  $\beta$ .



$$F(s) = \sum_{i=0}^n a_i s^i = 0, \quad a_i = f_i(\alpha, \beta).$$

Curve families of constant damping ratio and undamped natural frequency are commonly mapped into the  $\alpha, \beta$  parameter plane and used to infer system characteristics.

In the case of a system transfer function, however, the characteristic equation is formed from the denominator. The numerator is not included in the formulation. Therefore, full frequency-response information cannot be gained from using the characteristic equation in the parameter plane method. Thaler and Thompson developed a form of the transfer function which could be used in the parameter-plane method [3]. This transfer function form has been used by Glavis [4] and Staples [5] to make frequency-response plots and analyses of systems in which the coefficients contained linear combinations of  $\alpha$  and  $\beta$ .

The derivation of the transfer function form developed in Ref. 3 follows:

Let the system transfer function be given as

$$T(s) = \frac{N(s)}{D(s)}$$

where  $N(s)$  and  $D(s)$  are each of the form

$$N(s) = \sum_{i=0}^n a_i s^i$$



and the terms are nonlinear function of two parameters,  $\alpha$  and  $\beta$ . The squared magnitude function can be obtained from

$$m^2 = T(j\omega) \cdot T(-j\omega).$$

If the polynomials  $N(s)$  and  $D(s)$  are separated into their even and odd parts,

$$T(s) = \frac{N_e(s) + N_o(s)}{D_e(s) + D_o(s)},$$

$$T(-s) = \frac{N_e(s) - N_o(s)}{D_e(s) - D_o(s)}$$

and 
$$T(s) \cdot T(-s) = \frac{N_e(s)^2 - N_o(s)^2}{D_e(s)^2 - D_o(s)^2}.$$

From this it may be seen that both the numerator and denominator are even polynomials. When  $s = j\omega$  both numerator and denominator are even in  $\omega$ . Thus

$$m^2 = \frac{\sum_{i=0}^{\ell} A_i \omega^{2i}}{\sum_{k=0}^n B_k \omega^{2k}}$$

where  $A_i = f_i(1, \alpha, \beta, \alpha\beta, \alpha^2, \beta^2, \alpha^2\beta, \alpha\beta^2, \dots)$

and similarly for the  $B_k$  terms.

There are now four parameters present, alpha, beta, magnitude and omega. Any one may be expressed in terms of

the others and curves drawn depicting the various relationships among the parameters as defined by the transfer function. Phase versus omega may also be examined by rationalizing  $T(j\omega)$  and using the arctan relationship to solve for the angle.

Although the original motivation for the parameter plane was to analyze linear dynamic systems, the method may also be used to analyze nonlinear systems. Consider a linear system. One of its characteristics is that a sinusoidal input signal of a given frequency will be repeated throughout the system as a sinusoidal signal of the same frequency. This is not always true in a circuit containing nonlinear elements. In most cases though, the internal signals are at least periodic and have the same period as the input signal. These signals may therefore be represented by a Fourier series. Thus a frequency-response transfer function may be defined relating the fundamental component of the output signal to the input signal and may be used in the parameter-plane analysis of a nonlinear system. The nonlinearity is considered a parameter whose characteristic is defined by a locus of points in a parameter plane e.g.,  $\alpha$  versus transfer-function magnitude. The function  $\alpha(v)$  is assumed to vary slowly enough that it may be considered as "frozen" or fixed over the frequency range of interest.

Further, this parameter plane analysis logic may be reversed and the method used as a tool in the design of a

system. Thus a desired system response may be specified and the  $\alpha, \beta$  parameter variations necessary to produce this response determined by the method.

The parameter-plane method would be far too laborious if done by hand. Therefore, FORTRAN IV computer programs have been developed by the author which allow the frequency-response form of the parameter plane method to be used in the design of filters with nonlinear elements. The program details are contained in Appendix A.

### III. DESIGN OF FILTERS WITH NONLINEAR ELEMENTS

Filters with nonlinear elements may be designed by reference to parameter-plane plots of the voltage transfer function of the filter. The design may emphasize the magnitude response, the phase response or both. The nonlinear elements are represented as parameters  $\alpha$  and/or  $\beta$  and used in conjunction with the parameters of magnitude and of normalized radian frequency,  $\omega$ . A computer generates selected plots of any one parameter versus another with a third parameter held constant and the fourth incremented to form a family of curves. A fifth parameter, phase, may be plotted versus  $\omega$  for family parameters  $\alpha$  and  $\beta$ . The desired filter response is noted on these plots and the required characteristics of a particular nonlinear element determined.

From given specifications a particular type of filter circuit is chosen and the transfer function determined. For simplicity let the nonlinear element be represented by the  $\alpha$  parameter and be a function of output magnitude. Also assume that in this case the magnitude response is important while the phase response is not.

The computer is told to make a Bode plot of the linear response of the filter for each of a family of  $\alpha$  values and the response required by the specifications is overplotted by hand onto the same graph (see Figure 1). Each



alpha-omega coordinate point along the specification curve indicates what the value of alpha must be in order to satisfy the specifications. These coordinate points are then picked off and transferred by hand to a computer-generated parameter-plane graph of alpha versus magnitude where beta has been held constant and omega incremented to form the curve family (see Figure 2). The locus of hand-plotted points defines the required characteristics of the particular nonlinear element with respect to the circuit output magnitude. If the nonlinear element were a function of frequency, the coordinate points would have been hand transferred to a computer-generated parameter-plane graph of alpha versus omega with magnitude as the family parameter. This would determine the necessary frequency characteristics of the nonlinear element.

Filters with two or more nonlinear elements may require plotting points in the alpha-beta parameter plane (magnitude held constant and omega incremented or vice versa) to determine possible value trade-offs between the nonlinear elements. The curve plotted on the graph of parameter versus magnitude or omega would still be used to define the nonlinear element characteristics. These same procedures could be followed with the response emphasis on phase rather than on magnitude.

An additional consideration is necessary. The transfer function is the ratio of one voltage to another,  $E_2/E_1$ . Consequently, the plotted response is that of  $E_2$  with  $E_1$

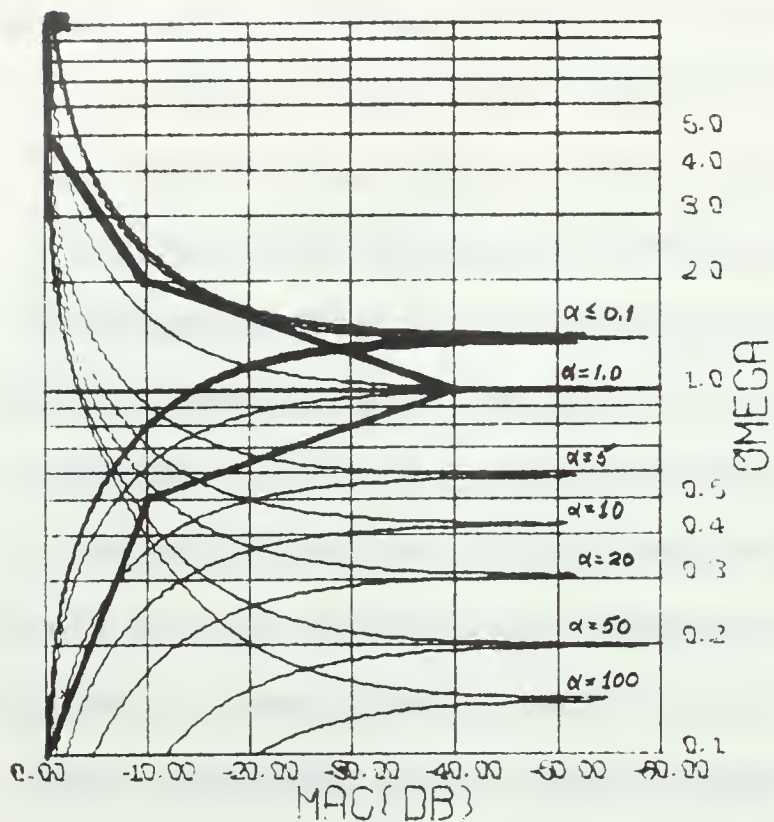


FIGURE 1.  
BODE PLOT WITH  
SPECIFICATION CURVE.

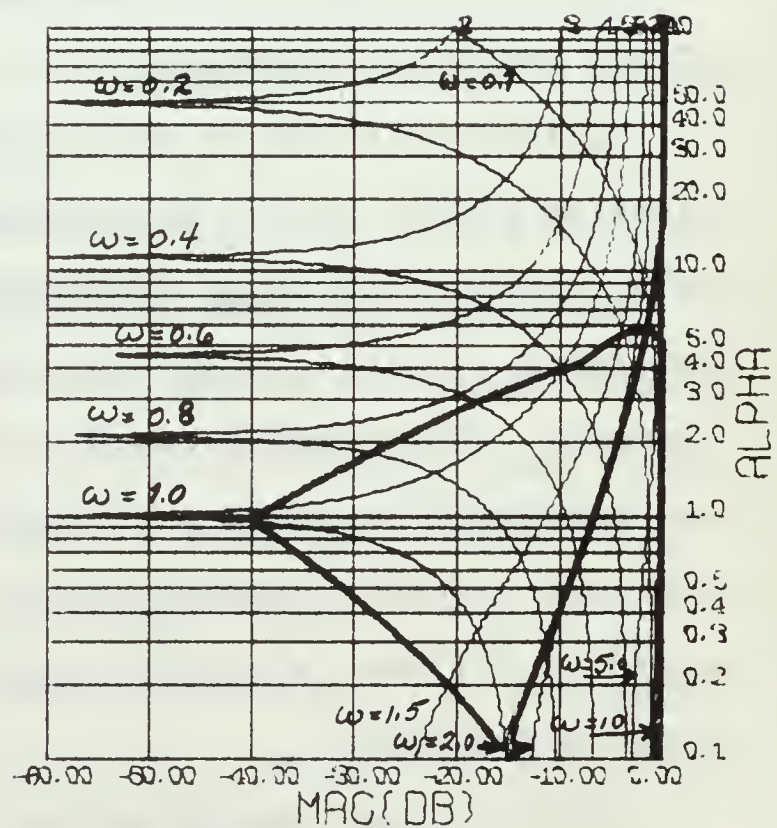


FIGURE 2.  
PARAMETER PLANE PLOT  
ALPHA VS MAGNITUDE.



set to one volt. Thus in realizing the filter design the nonlinear element must be made a function of  $E_2/E_1$  and not a function of  $E_2$  alone. A circuit to perform this division may be omitted if the nonlinear element is a function of frequency or when simulation sensitivity checks indicate that the filter response will be within acceptable limits for the predicted range of input values.

Although the filters considered here are shown in a lumped R - L - C configuration, the R, L and C should be looked upon as representing voltage-current relationships rather than actual physical components. The lumped R - L - C could be transformed into distributed values and/or L - C interchanges made through the use of active networks such as gyrators, mutators, rotators, etc. Time invariance is assumed however.

The steps in the design of a filter are:

1. Form the transfer function,  $T(s)$ , of the desired filter type designating the nonlinear elements as alpha, beta.
2. Determine which computer-generated plots will be needed.
3. Encode data and use the computer programs described in the appendix to generate the plots.
4. Select the Bode and/or phase plot as appropriate and draw in by hand the specified response curve.

5. Hand transfer the coordinate points along the response curve to the computer-generated parameter-versus-magnitude or parameter-versus-omega graphs.

6. Determine the characteristics of the nonlinear element from the locus of points plotted in step five above.

7. Check the design by computer simulation using several voltage input values to determine the effect of a changing input.

8. If the nonlinear element is a function of magnitude, decide whether or not the divider circuit is necessary.

9. Frequency shift the component values from the normalized radian frequency to the frequency of interest. Impedance shifting may also be used.

In the case of two or more nonlinear elements, step five will include the alpha-versus-beta plot for possible parameter value trade-offs.

#### A. FILTERS WITH ONE NONLINEAR ELEMENT

The following filter examples cover the four frequency types, lowpass, highpass, bandpass and band-reject. Each of these basic filters is made up of three elements, one R, one L and one C with the nonlinear element being a function of the output magnitude. The R element has been chosen as the nonlinear element since it may be readily associated with a field-effect transistor. The L or the C could just as well have been chosen.

### 1. Lowpass Filter

Figure 3 illustrates one possible lowpass filter configuration. Since frequency scaling will be employed as the last design step, the L and C values are normalized to one. The parameter alpha replaces the nonlinear element R. Thus the circuit transfer function is

$$T(s) = \frac{1}{1 + \alpha s + s^2} .$$

The necessary computer plots for the design of this circuit are the magnitude-versus-omega (Bode) and alpha-versus-magnitude plots.

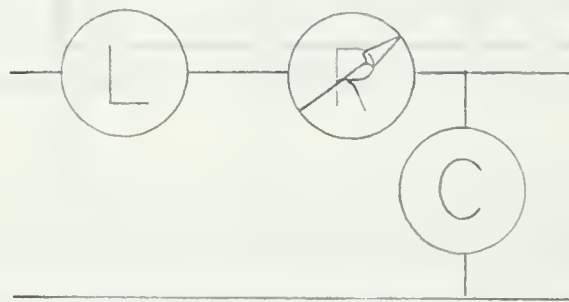


Figure 3. Lowpass Filter

Figure 4 is the Bode plot for the circuit. The alpha parameter curves on the plot indicate the output magnitude of the filter for the normalized radian frequency range of 0.1 to 10.0 radians when alpha is fixed at a particular parameter value. Thus if alpha were set equal to 1.0, the output-versus-frequency response of the filter would be that indicated by the curve for alpha equal to 1.0. Therefore, this graph illustrates the response of a linear filter

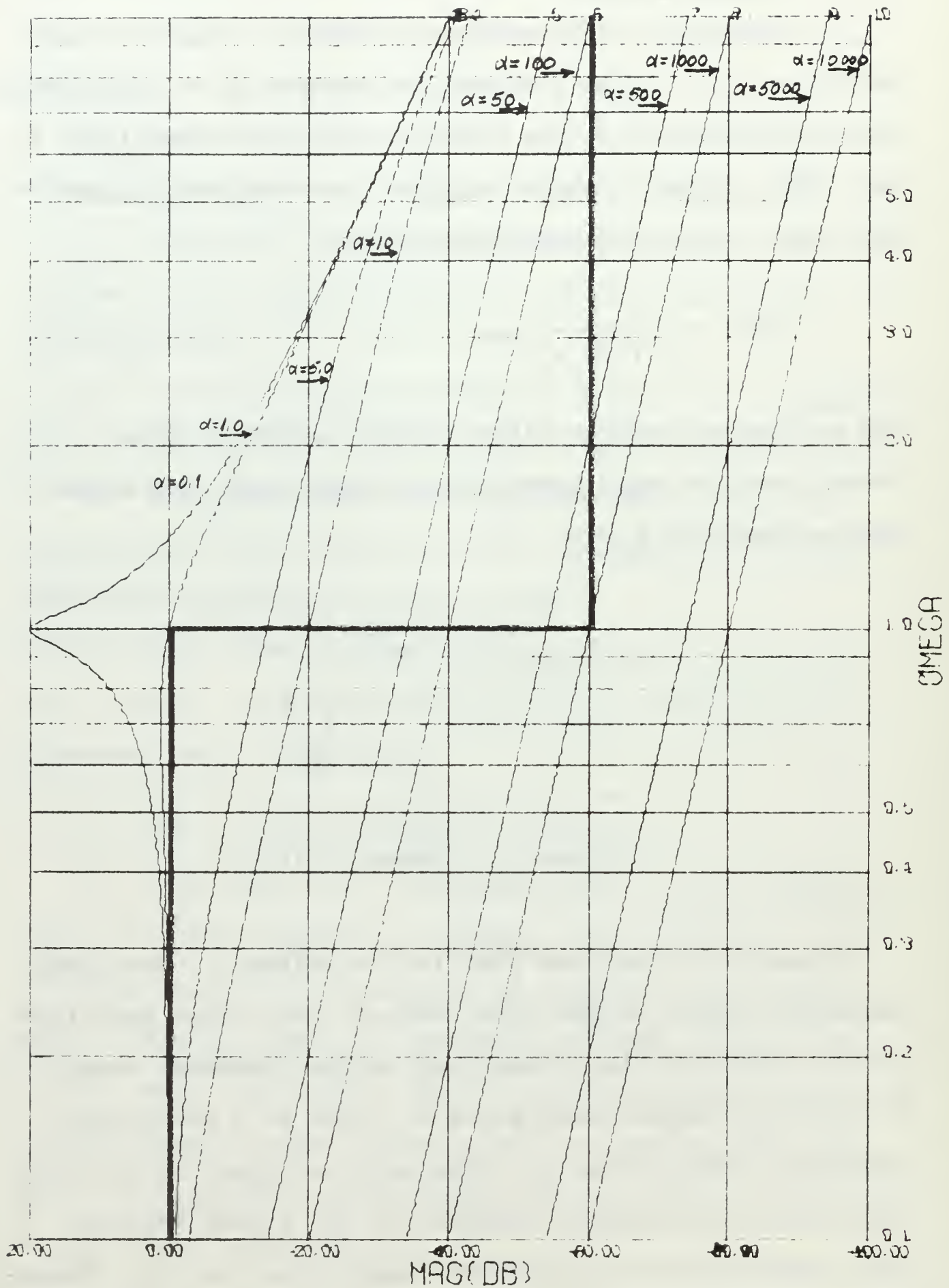


FIGURE 4.  
 R.A. NICHOLS, BODE PLOT, PARAMETER-ALPHA  
 LOWPASS FILTER,  $L=C=1.0$ ,  $R=ALPHA$



for several values of one of its elements,  $R$ . The filter specifications are indicated by the heavy line drawn on the graph by hand. In this case it is assumed to be the magnitude response of an ideal filter. The zero gain in the stopband of the ideal filter is represented by a line at the minus 60.0-dB level.

The coordinate points of the intersection of the alpha parameter curves and the desired response line in Figure 4 are picked off and transferred by hand to the alpha-versus-magnitude parameter-plane plot in step five of the design procedure. This plot is shown in Figure 5. The heavy line is the locus of points transferred. It indicates the desired characteristics of the nonlinear element when the value of the element is a function of the filter output magnitude.

The initial value of alpha for this plot is less than or equal to 2.0 at an omega of 0.1. The required value of alpha at cutoff is 1.0. For a flat, zero-dB response between these two omega points, required alpha values are 1.5 at an omega of 0.2 and 1.35 at an omega equal to 0.5. The plot also indicates that an alpha value of 1.0 would deviate from the ideal response by +1.0 dB at omega equal to 0.5 and less than about +1.2 dB between 0.5 and cutoff. If this is tolerable, alpha may be fixed at 1.0 for values of omega less than 1.0 and the design problem simplified.

In the region where omega is equal to 1.0 the alpha-magnitude relationship is logarithmic. The filter output

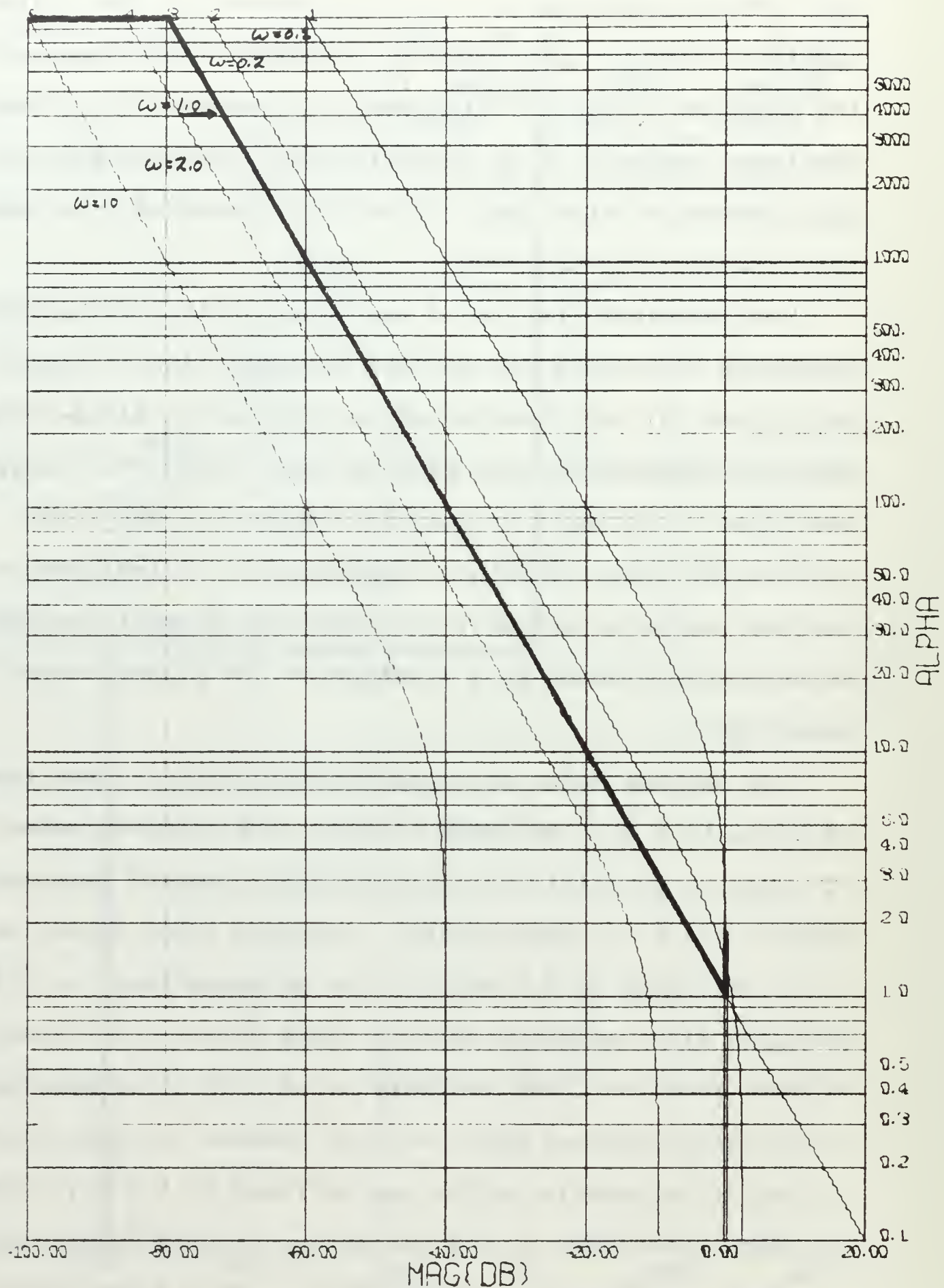


FIGURE 5.

R.A. NICHOLS, ALPHA VS MAGNITUDE (DB), PARAM=OMEGA  
LOWPASS FILTER, L=C=1.0, R=ALPHA



is 0.0 dB at alpha equal to 1.0, -60.0 dB at alpha equal to 1000 and -80.0 dB at an alpha of 10,000. The minus 60.0-dB level requires alpha to have a three-decade range in value. The minus 80.0-dB level is attainable with the four-decade range of field-effect transistors. Alpha may remain at this last value for frequencies above 1.0. If this is so, the output level will fall off at a 20-dB/decade rate.

At this point consideration should be given to the realization of the circuit. Although theoretically any function may be generated, the economics of the situation usually limits the degree of circuit complexity allowed and causes simplifying approximations to be investigated. The fixing of alpha at 1.0 for the frequency region below 1.0 and to a fixed value for the region above 1.0 would be simplifications in the case of the lowpass filter. The drop in output magnitude below 0.0 dB at cutoff when alpha is equal to 1.0 may be used to initiate the required parameter value change. The change in R could come from the filter transfer-function output voltage being subtracted from a fixed reference level and the difference applied to the gate of a field-effect transistor.

Figure 6 is the phase-plot companion to the Bode plot of Figure 4. The dark line indicates the expected phase response of the filter when alpha equals 1.0 at values of omega below 1.0 and equals 10,000 at omega values above 1.0.

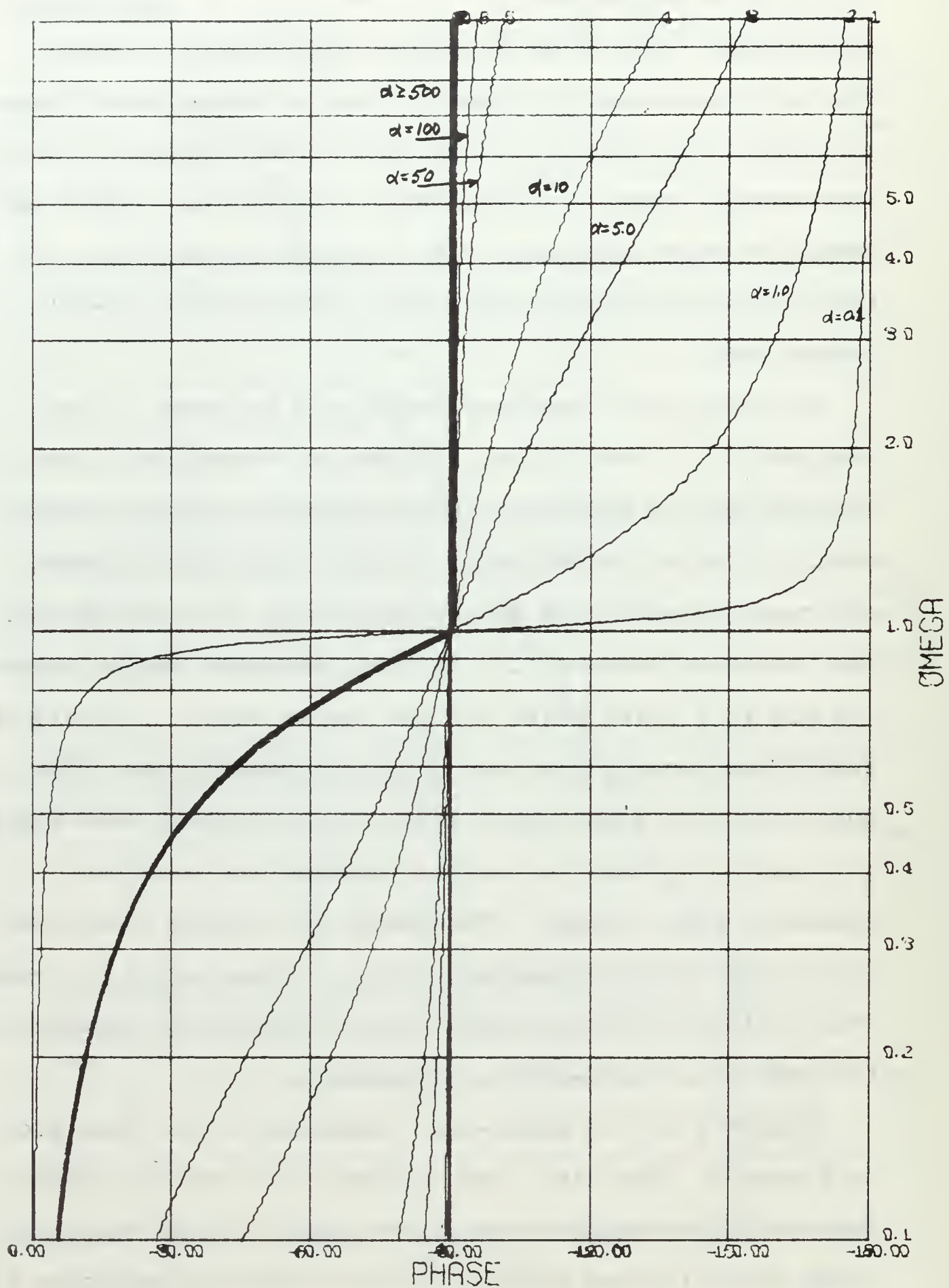


FIGURE 6.  
 R.A. NICHOLS, PHASE PLOT, PARAMETER=ALPHA  
 LOWPASS FILTER,  $L=C=1.0$ ,  $R=ALPHA$

The phase fall-off in the latter region is very slow. Designing for the ideal magnitude response does not yield a linear phase filter.

If  $\alpha$  were a function of frequency, the plot of  $\alpha$  versus  $\omega$ , Figure 7, would replace the  $\alpha$ -versus-magnitude plot. Again, the heavy line is the locus of points transferred from the Bode plot of Figure 4. The 0.0-dB curve defines the exact values of  $\alpha$  necessary for a completely flat magnitude response in the passband region. The area between the 0.0 and +1.0 dB curves indicates the latitude in  $\alpha$  values available for frequencies below 0.2 radians.

The computer simulation and input sensitivity check results are depicted in Figure 8 for the output magnitude and in Figure 9 for the phase. A 1.0-dB region of uncertainty or lag is assumed for the output level at which the parameter value change is initiated.  $\alpha$  is fixed at 1.0 for output values above the minus 1.0-dB level and allowed to go as far as 10,000 whenever the output drops below -1.0 dB. The curves represent the circuit response when the divider circuit is omitted and the input voltage varies around 1.0.

## 2. Highpass Filter

Figure 10 illustrates a possible highpass filter configuration. As in the lowpass filter circuit  $L$  and  $C$  are normalized to one and  $\alpha$  represents the nonlinear  $R$  in the transfer function

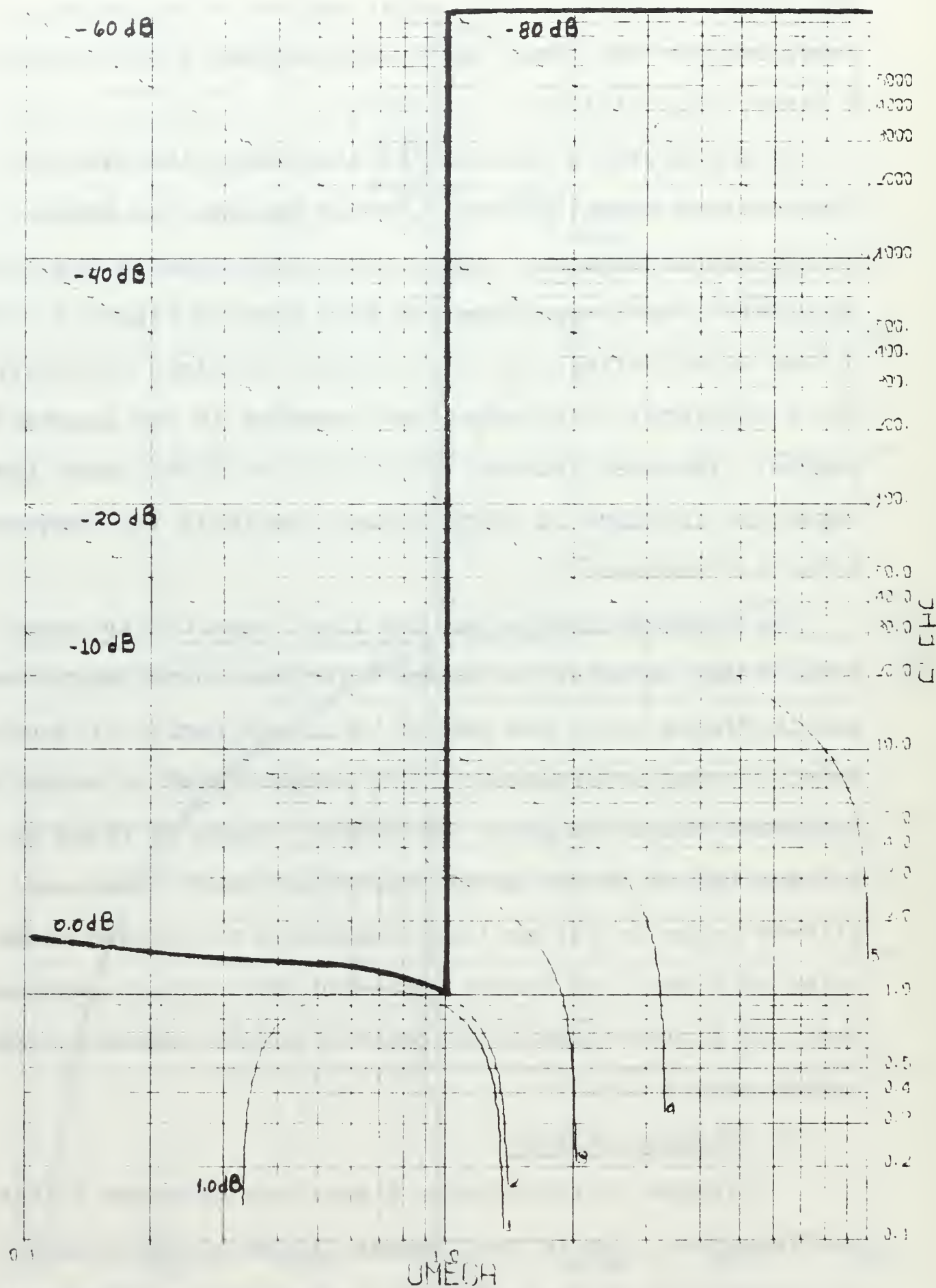


FIGURE 2.

R.A. NICHOLS, ALPHA VS OMEGA, PARAMETER=1116 (DB)  
LOWPASS FILTER, L=C=1.0, R=ALPHA



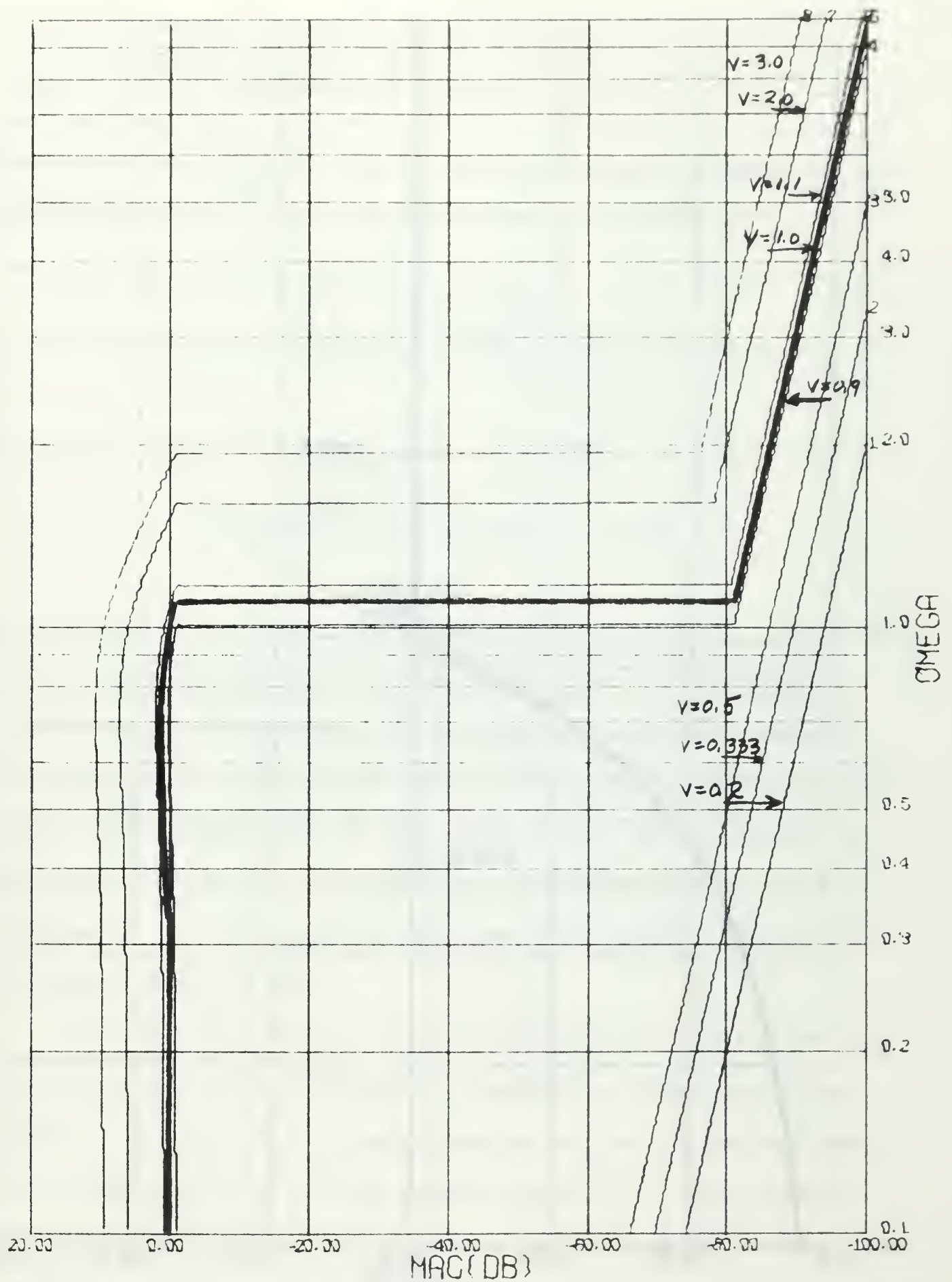


FIGURE 8.

R.A. NICHOLS, BODE PLOT, PARAMETER=(U[INPUT]\*1.0),  
LOWPASS FILTER,  $L=C=1.0$ ,  $R=ALPHA$

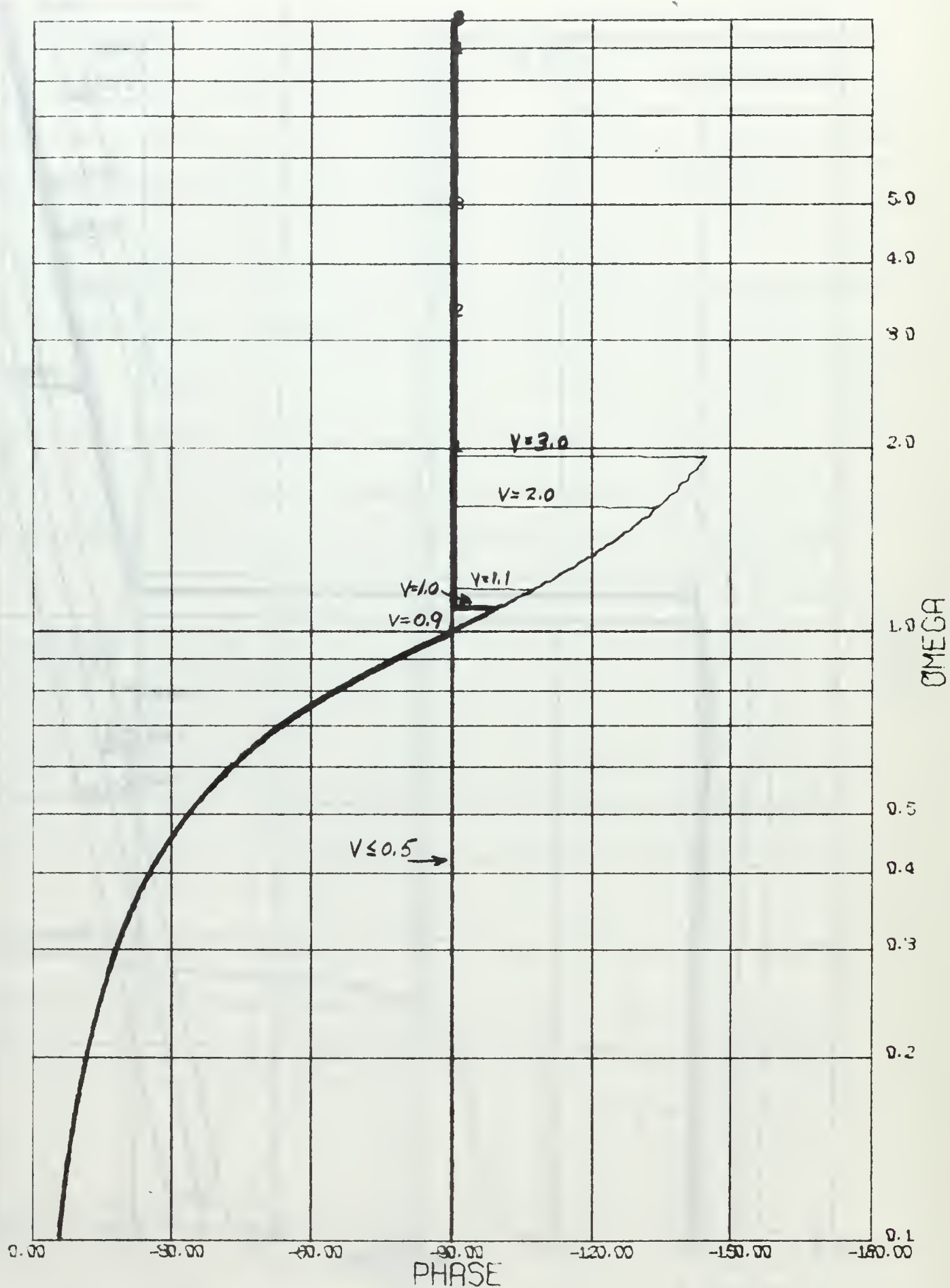


FIGURE 9.

R.A. NICHOLS, PHASE PLOT, PARAMETER=(UINPUT\*1.0).  
LOWPASS FILTER.  $L=C=1.0$ ,  $R=ALPHA$



$$T(s) = \frac{s^2}{1 + \alpha s + s^2} .$$

The necessary computer plots for the design of this filter are the Bode and the alpha-versus-magnitude plots

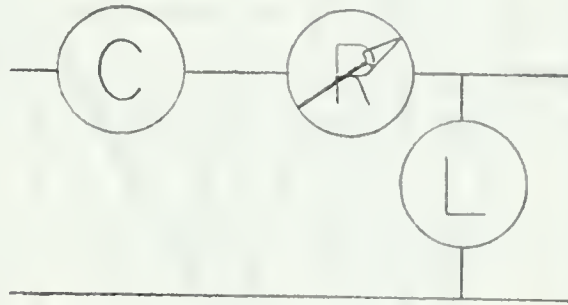


Figure 10. Highpass Filter

Figure 11 is the Bode plot for this circuit. Since the circuit configuration is related to that of the lowpass filter by an interchange of frequency-sensitive elements, the Bode plot is a reflection of the lowpass filter circuit about the omega equal to 1.0 axis. This relationship is further brought out by the alpha-versus-magnitude plot of Figure 12. It is exactly the same as Figure 5 except for reversed omega values.

Circuit realization is also related to that of the lowpass filter. In this case the parameter alpha could be fixed at 10,000 in the omega region below 1.0 and allowed to decrease to 1.0 in the region above 1.0. The filter transfer-function output would be added to a reference level and the sum applied to the gate of a field-effect transistor. The change in alpha would be initiated when the output magnitude exceeded a given value, say -80.0 dB.

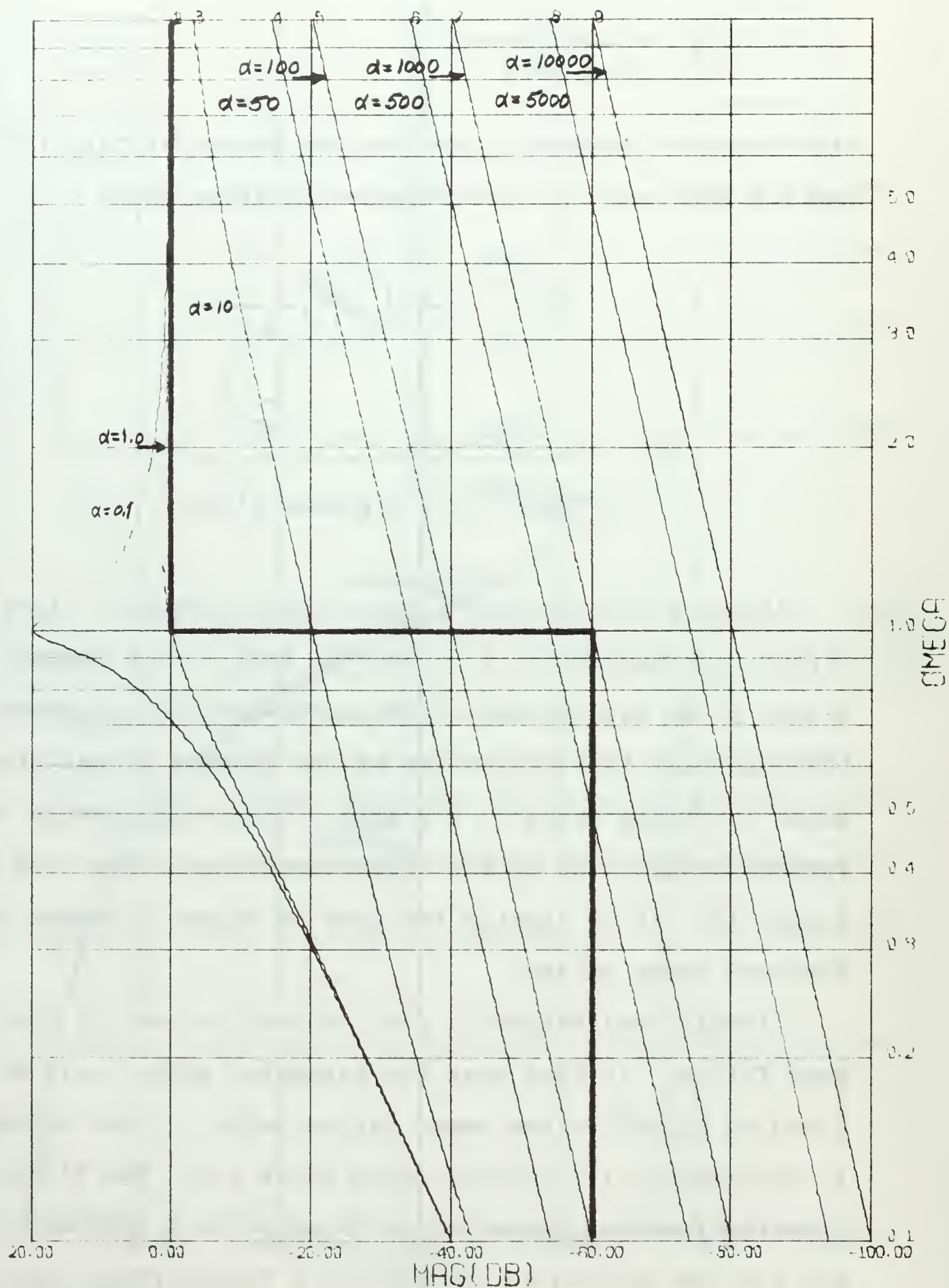


FIGURE 11.

R.A. NICHOLS, BODE PLOT, PARAMETER=ALPHA  
HIGHPASS FILTER,  $L=C=1.0$ ,  $R=ALPHA$

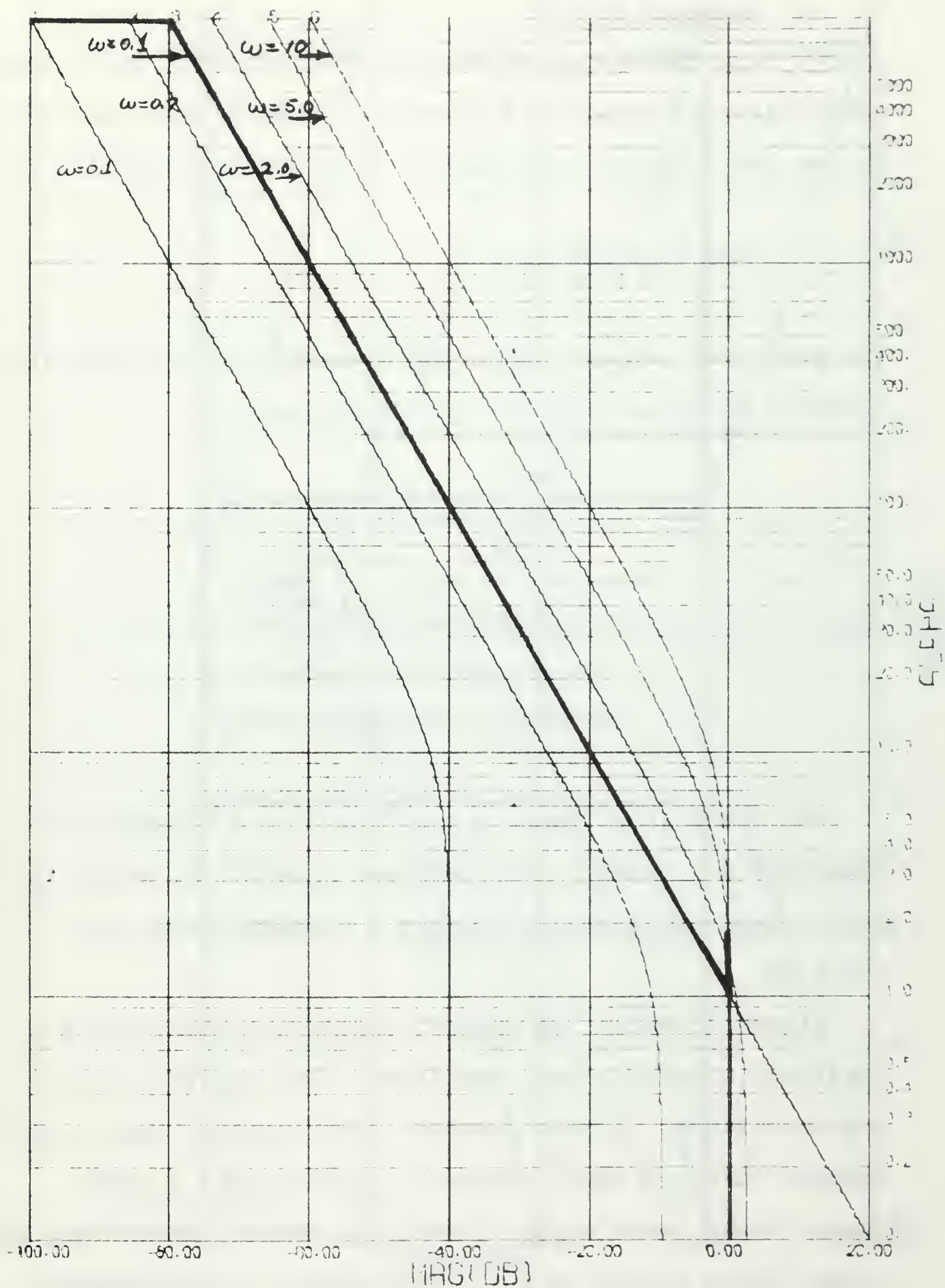


FIGURE 12.

R.H. NICHOLS, ALPHA VS MAGNITUDE (DB), PARAM=ONEUR  
 HIGHPASS FILTER, L=C=1.0, R=ALPHA

### 3. Bandpass Filter

The three-element circuit configuration for a bandpass filter is shown in Figure 13. Again L and C are set to one and R replaced by alpha. The transfer function is

$$T(s) = \frac{\alpha s}{1 + \alpha s + s^2} .$$

The Bode plot and the alpha-versus-magnitude plot are the computer plots used in the filter design.

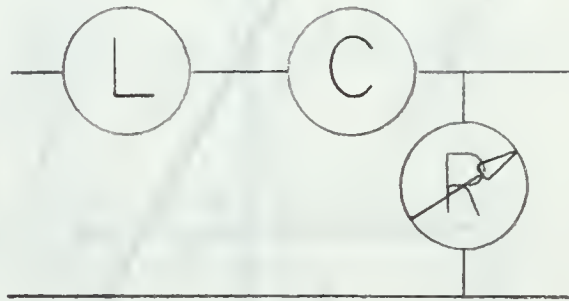


Figure 13. Bandpass Filter

The heavy line drawn on the Bode plot of Figure 14 specifies a 1.0-omega-wide bandpass symmetrical about the point where omega equals 1.0 and a stopband level of -60.0 dB.

Figure 15 shows the specifications in terms of the nonlinear element versus magnitude. The desired alpha characteristics in this case are more complex than in the lowpass case. A small change in alpha causes a large output change when alpha, itself, is small. When alpha is large, which is the case in the passband, large parameter value changes are necessary to affect the output. This



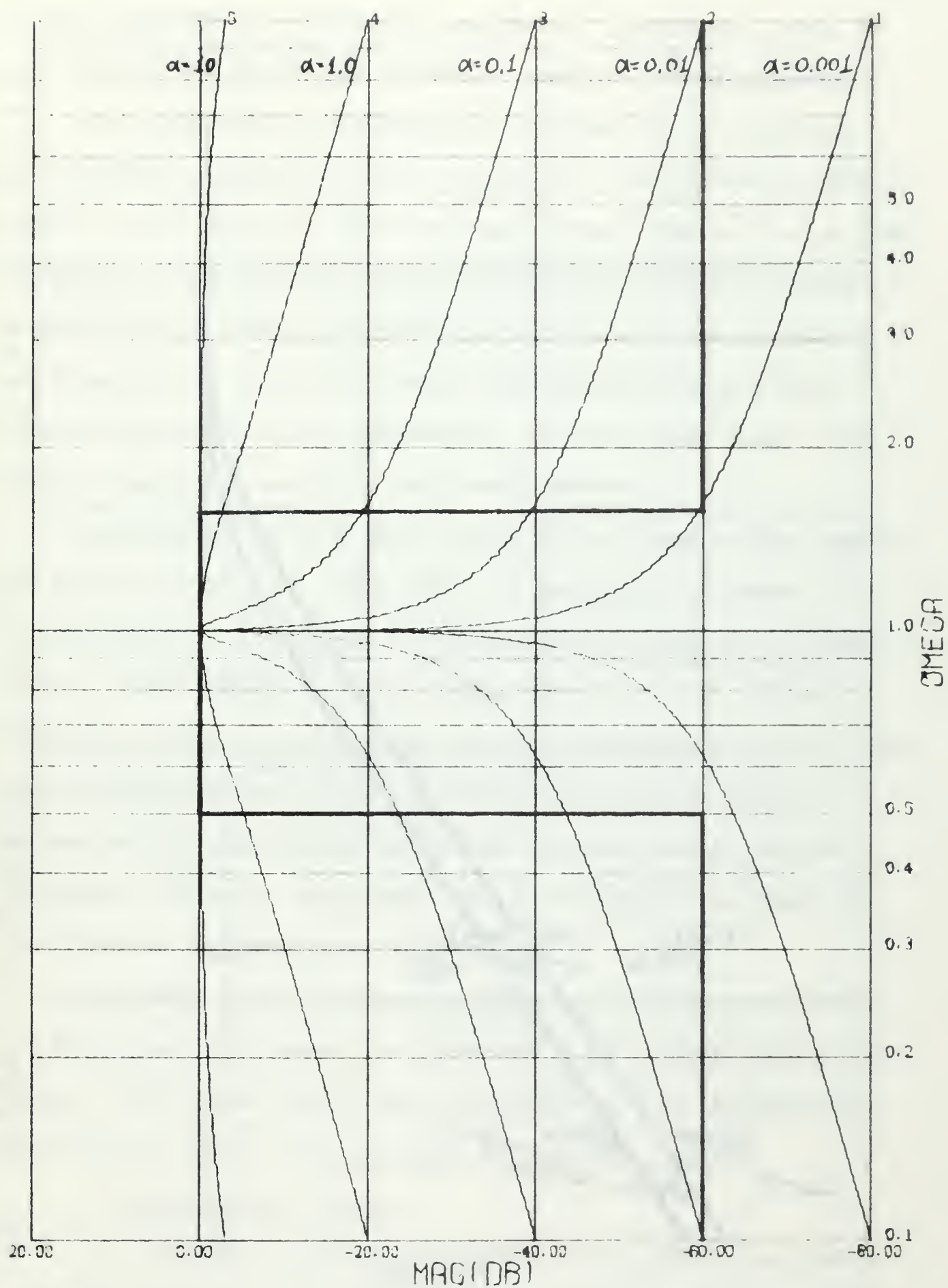


FIGURE 14.

R.A. NICHOLS, BODE PLOT, PARAMETER=ALPHA  
BANDPASS FILTER,  $L=C=1.0$ ,  $R=ALPHA$



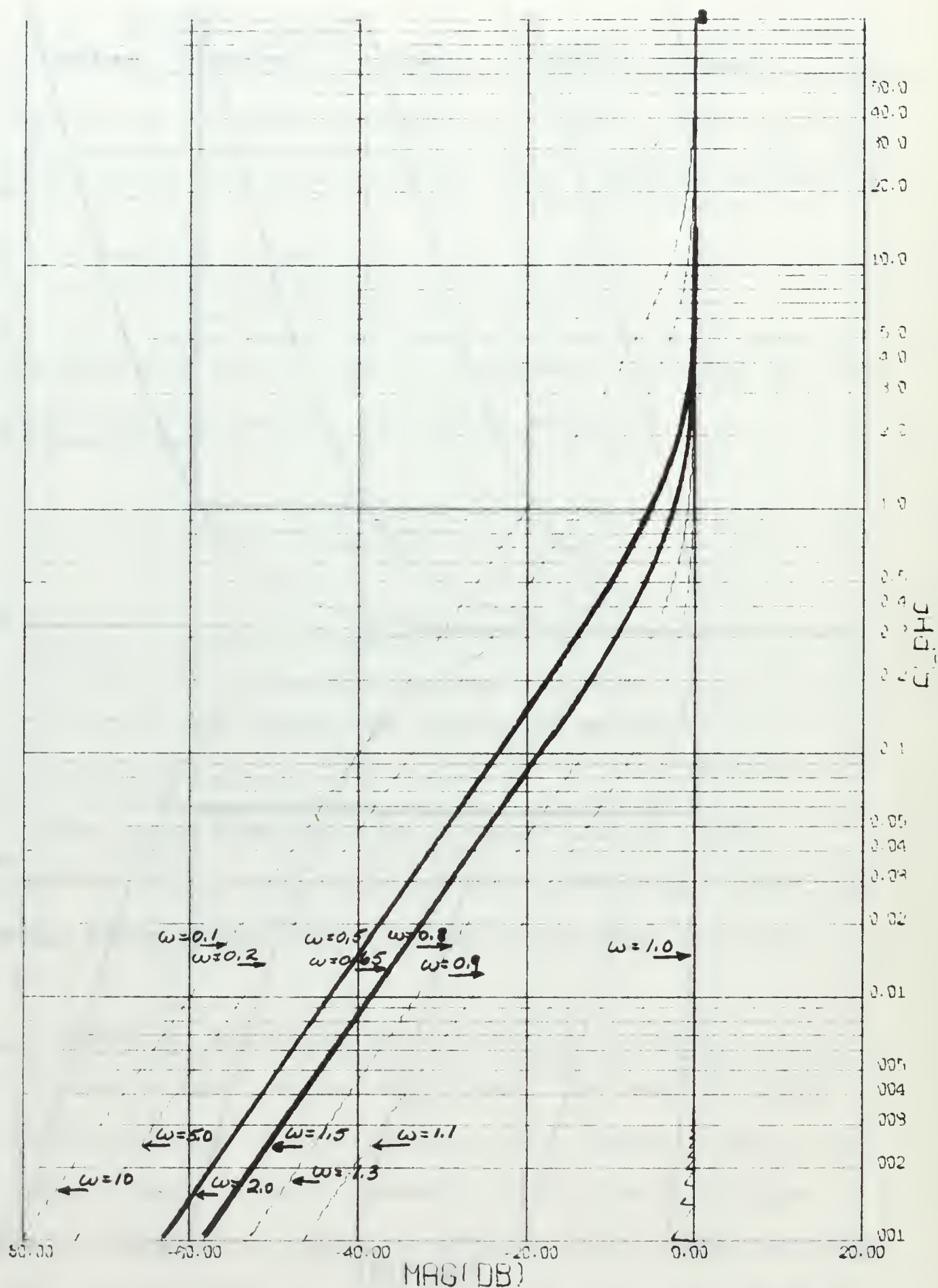


FIGURE 15.  
 R.A. NICHOLS, ALPHA VS MAGNITUDE (DB), PARAM=OMEGA  
 BANDPASS FILTER, L=C=1.0, R=ALPHA

would indicate a relatively unstable attenuation level in the stopband region but a stable level in the passband.

The width of the passband is limited by the minimum attenuation required in the stopband. The wider the passband, the higher the maximum alpha value must be for a flat response. The range of values available with the chosen element would then indicate the point where the stopband attenuation is too low to meet specifications and thus limit the width of the passband. On the other hand, the filter passband could be made very narrow.

Realization of the filter can not be done on the basis of magnitude alone. Some sort of frequency or phase sensing device is needed to determine the region of operation, either above or below  $\omega$  equal to 1.0. Given a frequency sensor the circuit could be formed by letting the magnitude response level crossing initiate the alpha parameter value changes to define the end points of the passband. This is the same type of operation as used in the lowpass and highpass filters.

The phase plot is shown in Figure 16. The zero phase-shift region indicates the passband where alpha values are large. The phase below the passband would be 90 degrees leading and above the passband 90 degrees lagging.

#### 4. Band-Reject Filter

A three-element band-reject filter is illustrated in Figure 17. The transfer function when L and C are set to one and R replaced by alpha is

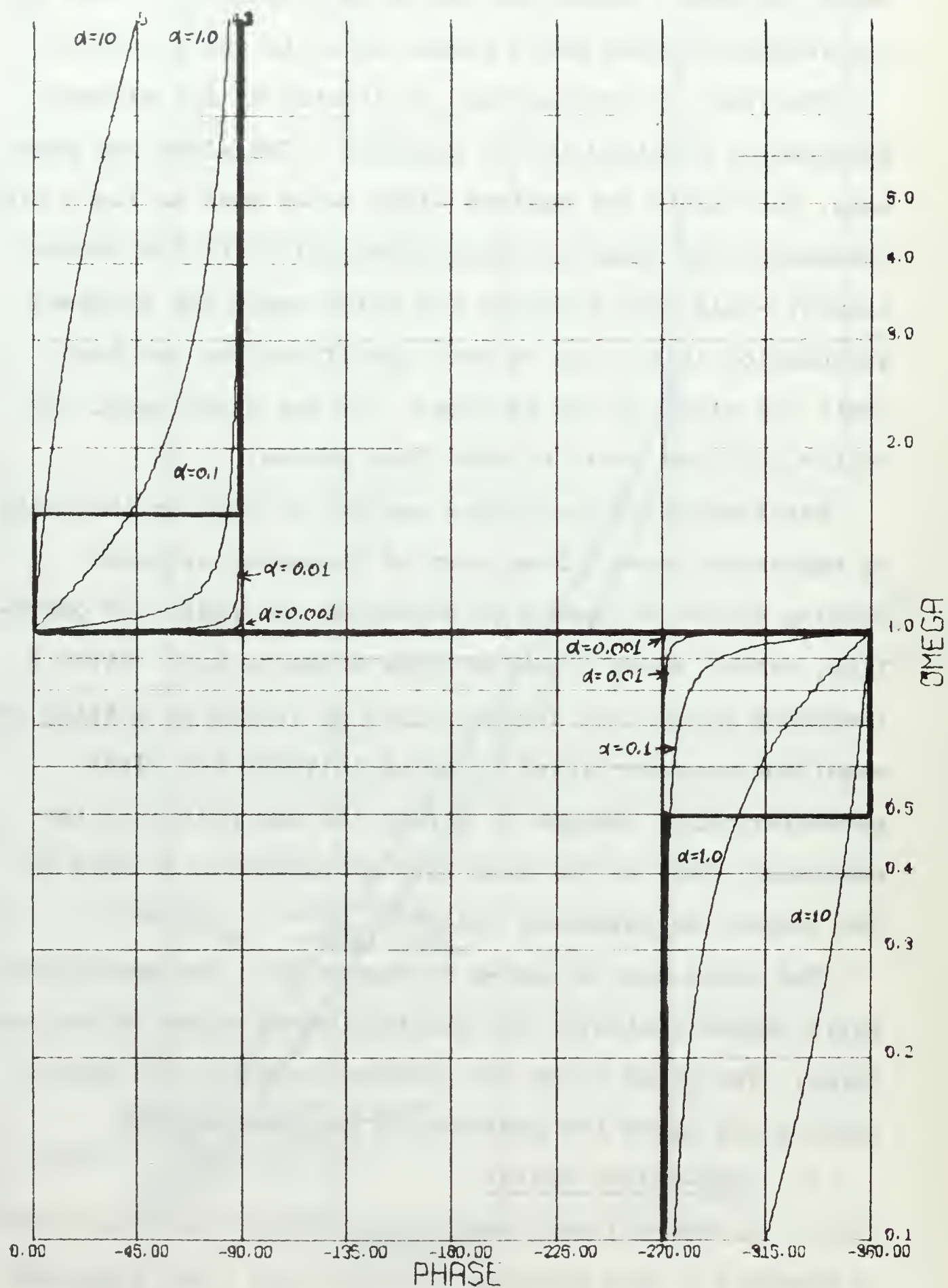


FIGURE 16.

R.A. NICHOLS, PHASE PLOT, PARAMETER=ALPHA  
BANDPASS FILTER,  $L=C=1.0$ ,  $R=ALPHA$



$$T(s) = \frac{1 + s^2}{1 + s + s^2} .$$

The design of the filter calls for Bode and alpha-versus-magnitude plots.

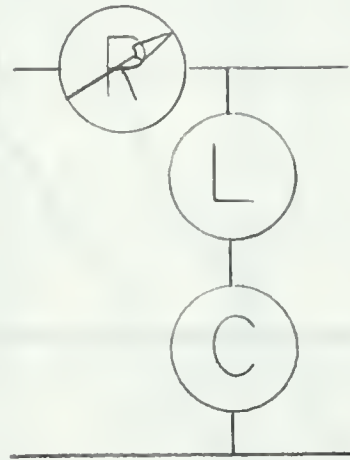


Figure 17. Band-Reject Filter

The specifications are indicated on the Bode plot, Figure 18, and the alpha-versus-magnitude plot, Figure 19. The phase plot is shown in Figure 20. The plots confirm the expected, that the band-reject filter is the inverse of the bandpass filter.

As in the case of the bandpass filter, the band-reject filter can not be realized by using magnitude response alone. It too must have a frequency or phase sensor to indicate the region of operation.

#### B. FILTERS WITH MORE THAN ONE NONLINEAR ELEMENT

More complex filters may be formed using more than one nonlinear element. They may be built up by combining filter

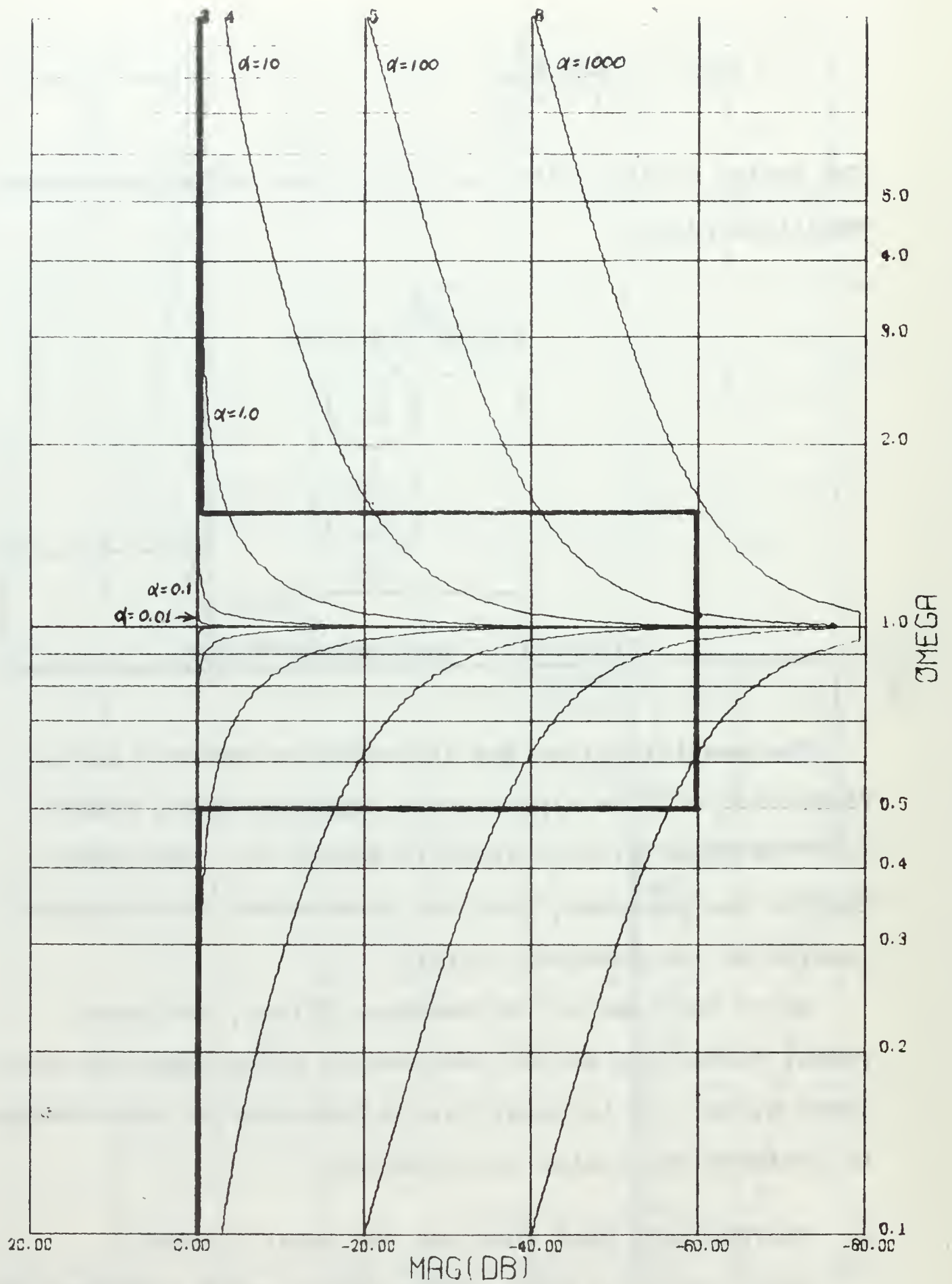


FIGURE 18.

R.A. NICHOLS, BODE PLOT, PARAMETER=ALPHA  
BAND-REJECT FILTER,  $L=C=1.0$ ,  $R=ALPHA$ .



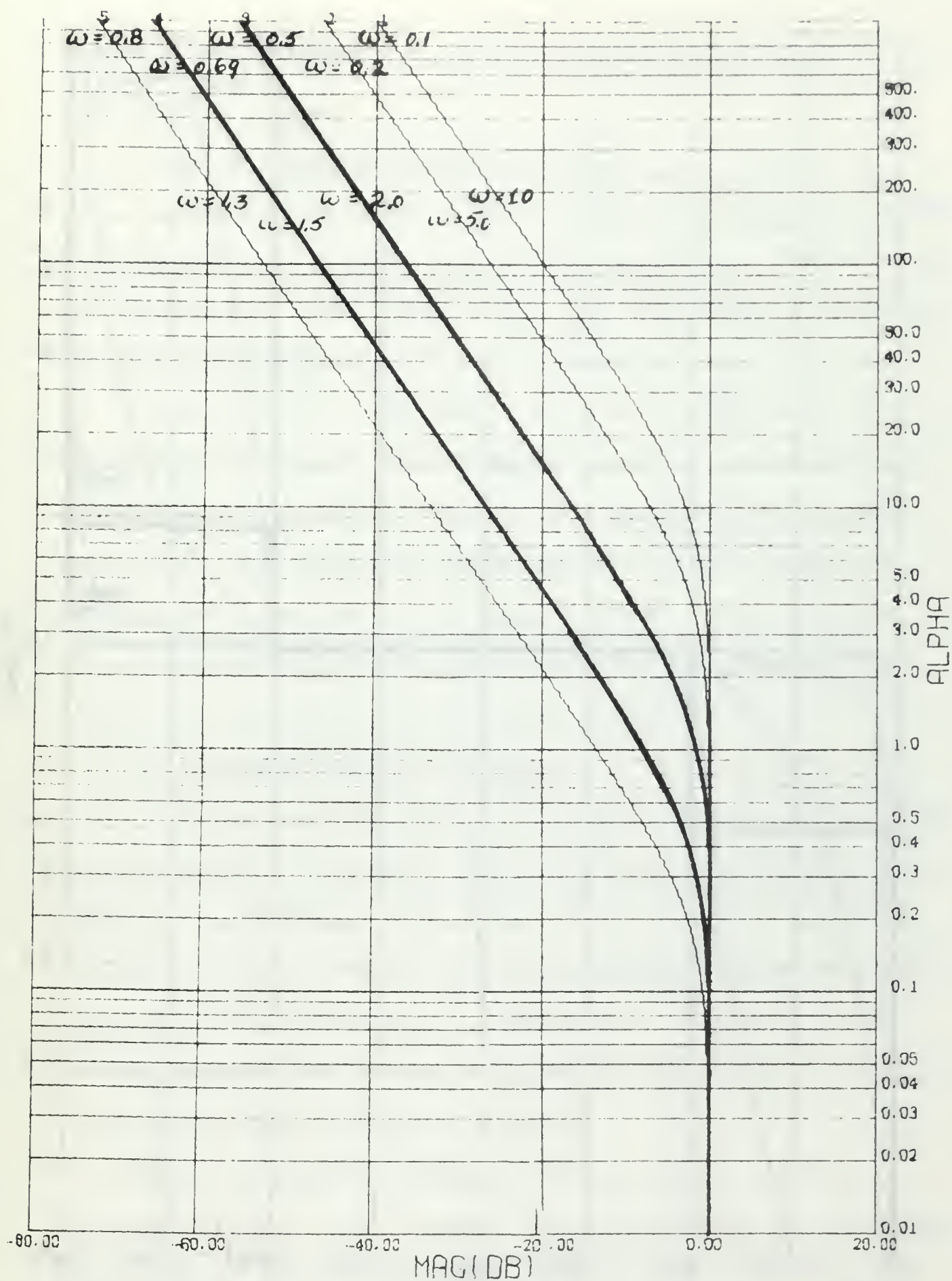


FIGURE 19.  
R.A. NICHOLS, ALPHA VS MAGNITUDE (DB), PARAM=OMEGA  
BAND-REJECT FILTER, L=C=1.0, R=ALPHA.

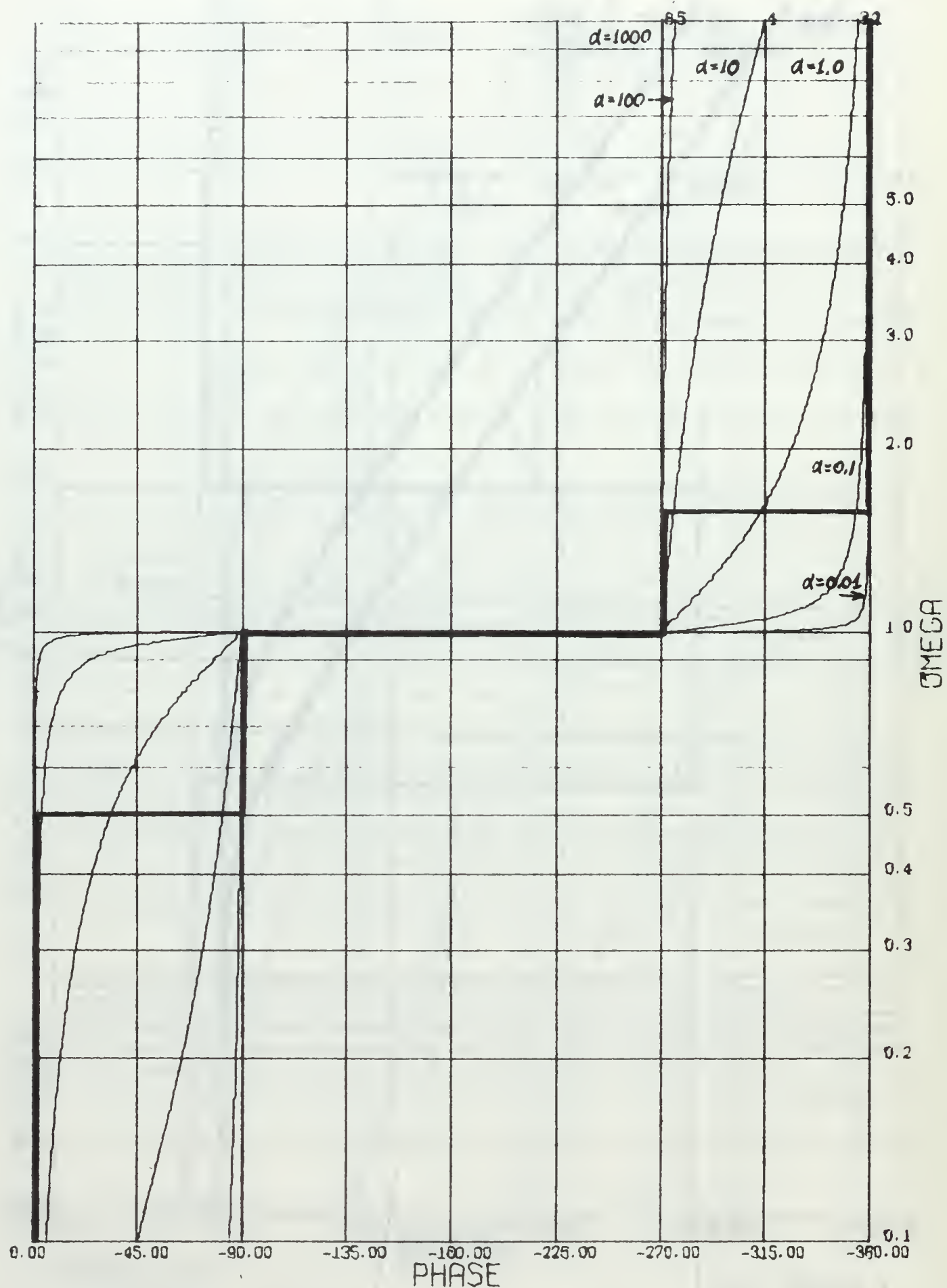


FIGURE 20.

R.A. NICHOLS, PHASE PLOT, PARAMETER=ALPHA  
BAND-REJECT FILTER,  $L=C=1.0$ ,  $R=ALPHA$ .

sections and/or by using several nonlinear elements in the same section.

### 1. Concatenating Filter Sections

Additional attenuation of undesired frequencies may be obtained by concatenating filter sections. The sections are designed as individual units and then coupled together by buffer amplifiers.

A considerable improvement over the single-section design of a bandpass filter may be made by concatenating lowpass and highpass sections. The passband end points are set in the frequency shifting step by the amount of HP-LP cutoff frequency overlapping used. A band-reject filter may be designed by inverting the bandpass filter output and adding it to the input signal.

### 2. Cascading Filter Sections

There are two types of cascaded filters. The first type consists of those in which the nonlinear element in each section is made a function of the transfer ratio of the total filter. This type also includes those filters in which the nonlinearity is a function of frequency since this parameter, or at least its first Fourier approximation, is common to the filter as a whole.

Figure 21 shows an example of this first type of cascaded filter. Two lowpass filter sections are cascaded with both  $R_1$  and  $R_2$  functions of the total filter output magnitude.  $R_1$  equals  $k$  times  $R_2$ . Setting  $L$ ,  $C$  and  $k$  to



one and replacing the R's with alpha gives a transfer function of

$$T(s) = \frac{1}{2\alpha s + (2 + \alpha^2)s^2 + 2\alpha s^3 + s^4}$$

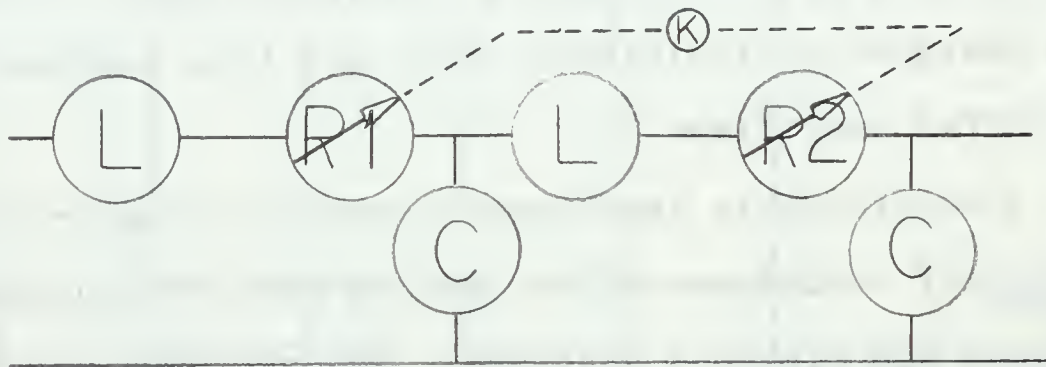


Figure 21. Cascaded Filter Sections, Type 1.

This type of cascaded filter is designed as a single filter since the transfer function contains only one parameter, alpha and it is a function of magnitude. The Bode plot for this circuit is shown in Figure 22, the alpha-versus-magnitude plot in Figure 23 and the phase plot in Figure 24. The specifications are assumed to be the same as those for the single-sections lowpass filter except that the stopband attenuation is now set to -120.0 dB.

In this filter design there is no simple approximation which would give a reasonably flat response below cutoff. The alpha value must change smoothly from 5.0 at omega equal to 0.1 to 0.1 at omega equal to 1.0. The relationship of alpha to magnitude in the omega equal to 1.0 cutoff region is shown in Figure 23. This is not a simple logarithmic

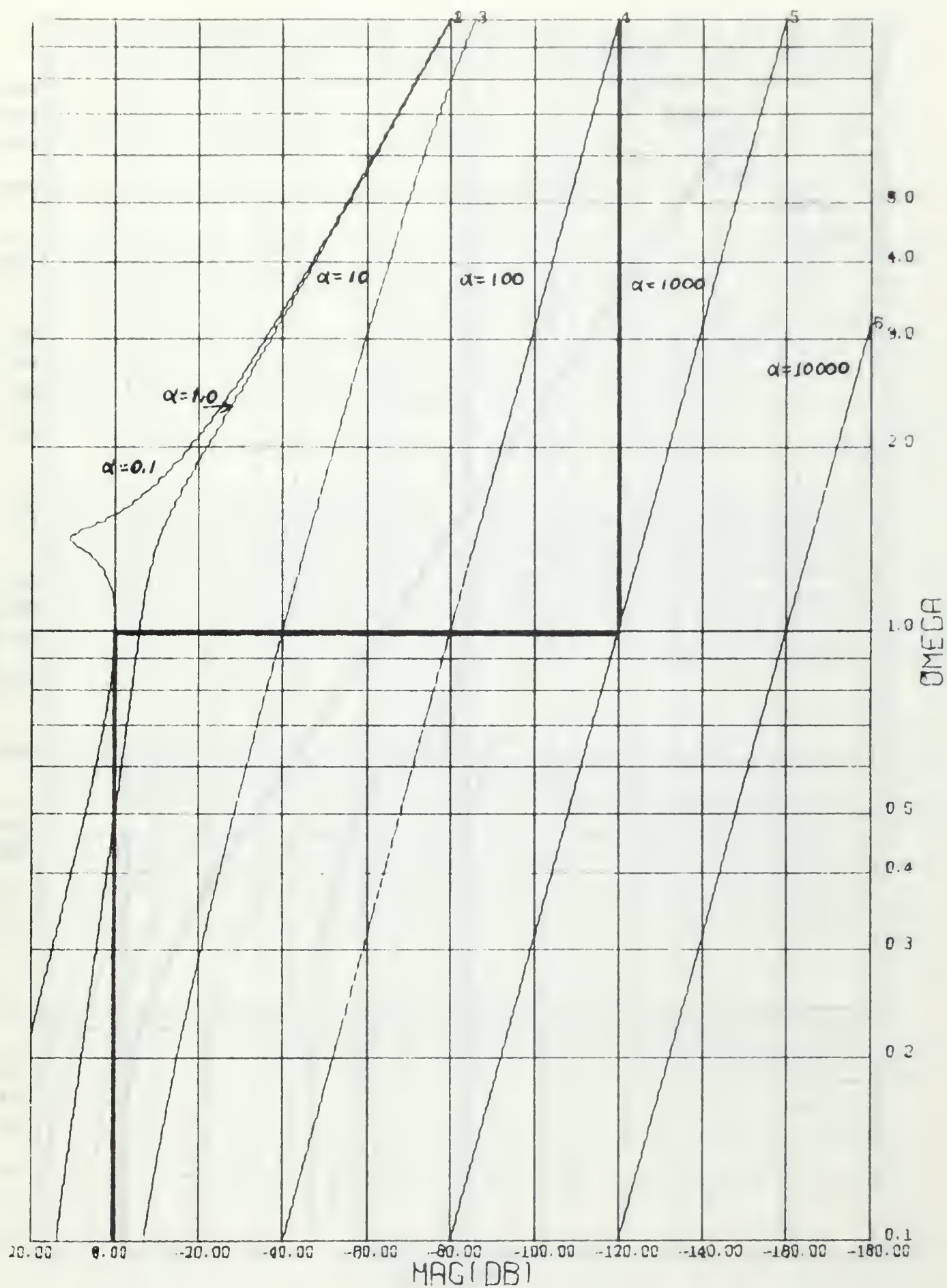


FIGURE 22.

R.A. NICHOLS. BODE PLOT. PARAMETER=ALPHA=R  
2-LP SECTIONS CASCADED. TYPE 1. L=C=1.0



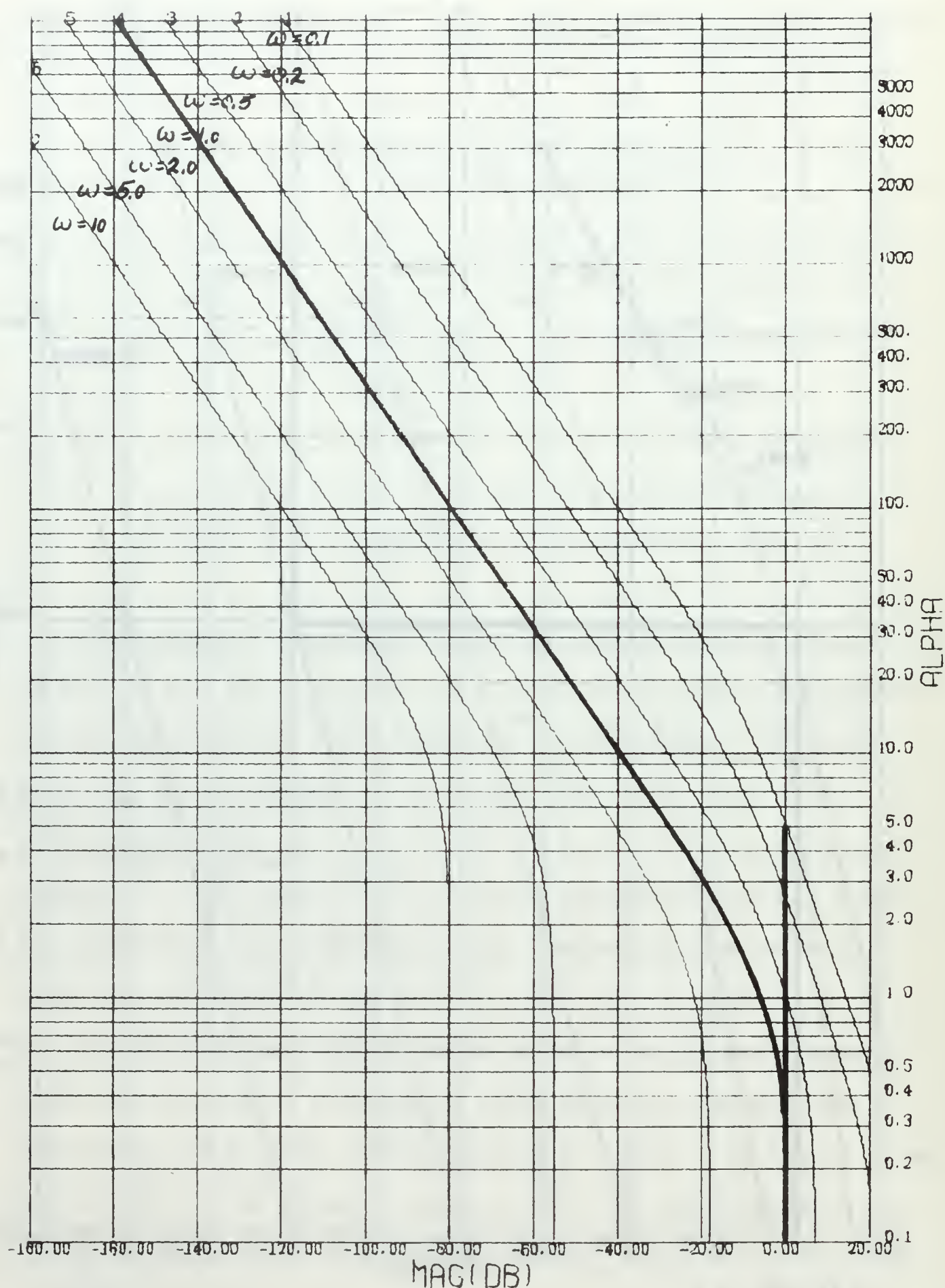


FIGURE 23.

R.A. NICHOLS, ALPHA(R) VS MAG (DB), PARAM=OMEGA  
 2-LP SECTIONS CASCADED, TYPE 1, L=C-1.0

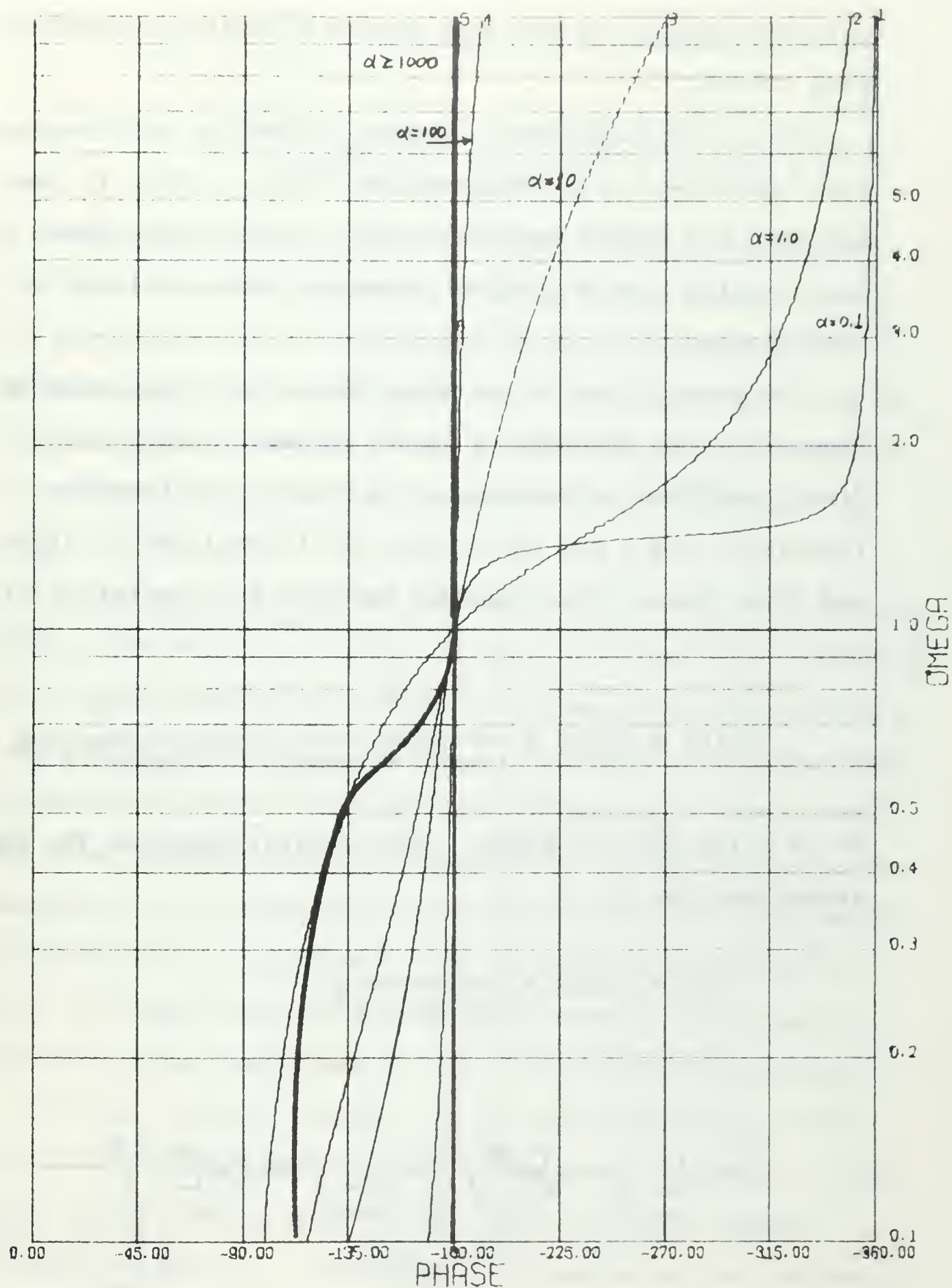


FIGURE 24.

R.A. NICHOLS, PHASE PLOT. PARAMETER=ALPHA(R)  
2-LP SECTIONS CASCADED. TYPE 1. L=C=1.0

relationship as was the case with the single-section low-pass filter.

This type-1 cascaded, lowpass filter has an advantage over the two-section concatenated filter in that it does not need the buffer amplifier; but, on the other hand, it does require a more complex parameter characteristic in the passband.

The second type of cascaded filter is illustrated in Figure 25. It consists of those filters formed by the direct addition of sections. In forming the transfer function  $L$  and  $C$  are set to one,  $R_1$  is replaced by  $\alpha$  and  $R_2$  by  $\beta$ . The transfer function for the total filter is

$$T(s) = E_3/E_1 = \frac{1}{(\alpha+\beta)s + (2+\alpha\beta)s^2 + (\alpha+\beta)s^3 + s^4}.$$

$R_2$  is a function of  $E_3/E_2$ . The transfer function for this second section is

$$T(s) = E_3/E_2 = \frac{1}{1 + \beta s + s^2}.$$

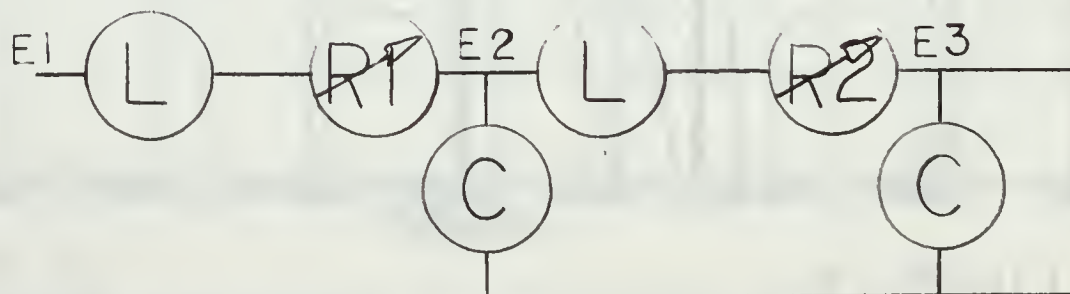


Figure 25. Cascaded Filter Sections, Type 2



In addition,  $R_1$  is a function of  $E_2/E_1$  so that

$$T(s) = E_2/E_1 = \frac{1 + \beta s + s^2}{(\alpha + \beta)s + (2 + \alpha\beta)s^2 + (\alpha + \beta)s^3 + s^4}.$$

A Bode plot for the  $E_3/E_1$  transfer function is shown in Figure 26. The parameter is  $\alpha$  with  $\beta$  set to 1.0. The specification curve is drawn in as in the previous examples with the stopband gain level at -120.0 dB. Due to the  $\alpha/\beta$  symmetry in the transfer function, Figure 26 is also valid for  $\beta$  as the parameter with  $\alpha$  set to 1.0.

$R_1$  is a function of an internal voltage-transfer ratio,  $E_2/E_1$ . The method of design in this case may be illustrated by assuming that  $R_2$  is a fixed value and that  $R_1$  is the only nonlinear element in the circuit. As before, the  $\alpha$ - $\omega$  coordinate points of the desired response curve are picked off from the Bode plot and transferred to the  $\alpha$ -versus-magnitude plot illustrated in Figure 27 and the required  $R_1$  characteristics determined. The only difference here is that the magnitude used is the  $E_2/E_1$  voltage ratio rather than the output magnitude of the  $E_3/E_1$  transfer function.

In this filter, however,  $R_2$  is also nonlinear so the plot of  $R_2$  versus  $E_3/E_2$  magnitude must be considered. This plot is the same as that of the single-section lowpass filter in Figure 5. Therefore, realization of the passband region may be simplified by setting  $R_2$  at 1.0 and causing  $R_1$  to follow the characteristic curve in Figure 27. The values



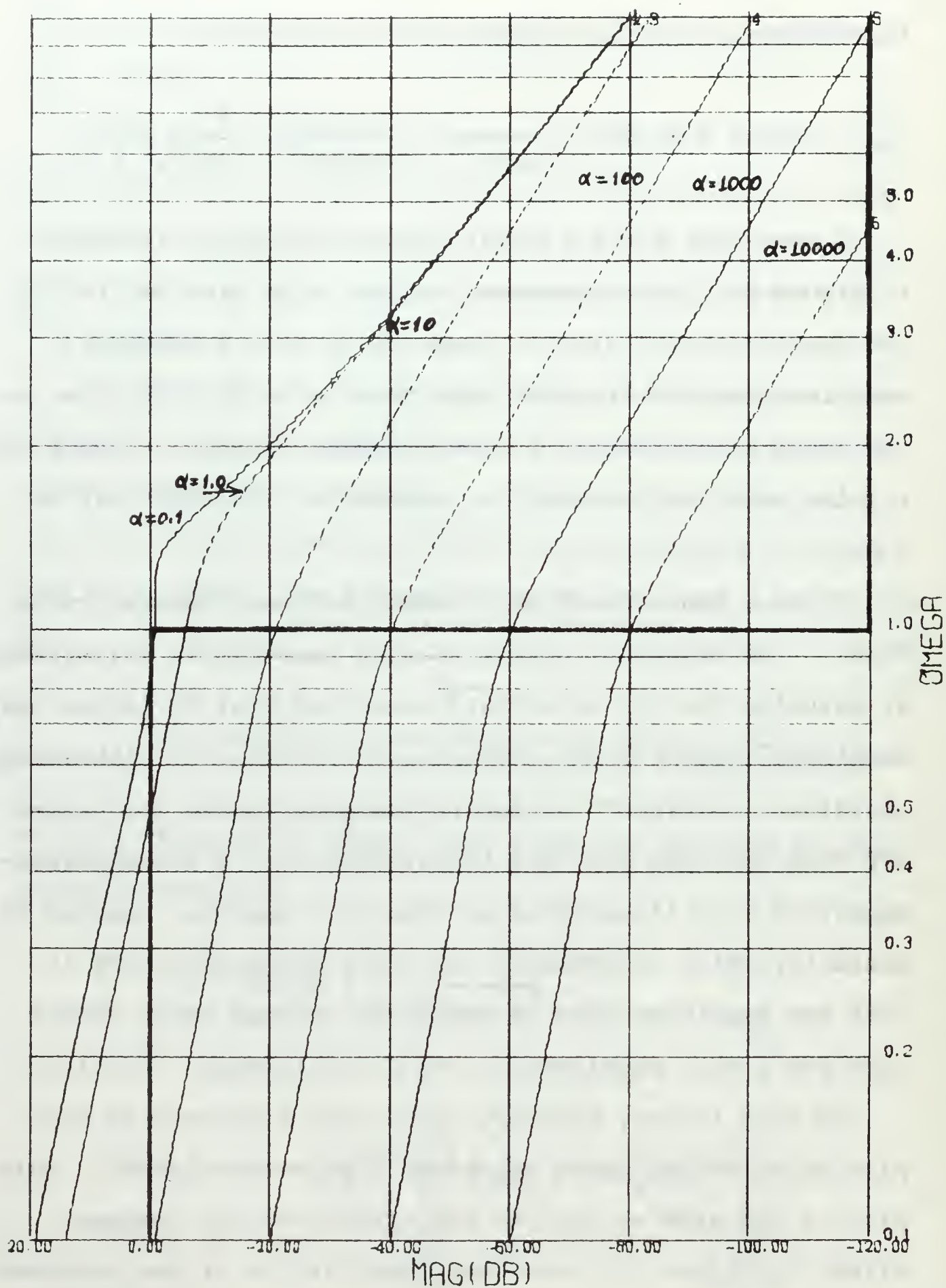


FIGURE 26.

R.A. NICHOLS, BODE PLOT, PARAMETER=ALPHA=R1  
(E3/E1), 2-LP SECTIONS CASCADED. R2=BETA=1.0=L=C.



of  $\alpha$  to be used in the passband region are determined from Figure 28. This figure is a plot of  $\alpha$  versus  $\beta$  for passband frequencies where the filter output magnitude is 0.0 dB.

In the cutoff region  $R_1$  and  $R_2$  change from their passband low values to their stopband high values.  $R_2$  follows the  $\omega$  equal to 1.0 logarithmic curve to the minus 80.0-dB level at  $\beta$  equal to 10,000. A four-decade range  $R_1$  element goes from 0.1 at 0.0 dB to 1000 at -60.0 dB. In so doing it follows the hand-drawn curve in Figure 29. This curve is a composite of the line for  $\omega$  equal to 1.0 in Figure 27 where  $R_2$  equals 1.0 and that of Figure 29 where  $R_2$  equals 10,000. The chosen values are determined from the  $E_2/E_1$   $\alpha$ -versus- $\beta$  plot of Figure 30 where  $\omega$  is fixed at 1.0 and output magnitude is the curve family parameter.

In the stopband region  $R_1$  may be left at 1000 and  $R_2$  at 10,000. The resultant attenuation at cutoff is -140.0 dB from which it falls off at 40 dB/decade. Figure 31 is the Bode plot of  $E_3/E_1$  for the stopband region above  $\omega$  equal to 1.0.

Figure 32 illustrates the phase response for passband values of  $\alpha$  and  $\beta$  while Figure 33 shows the phase response for stopband values.

Figure 34 and 35 show what the output magnitude and phase response would have been if two lowpass circuits had been added together directly. The response is not the



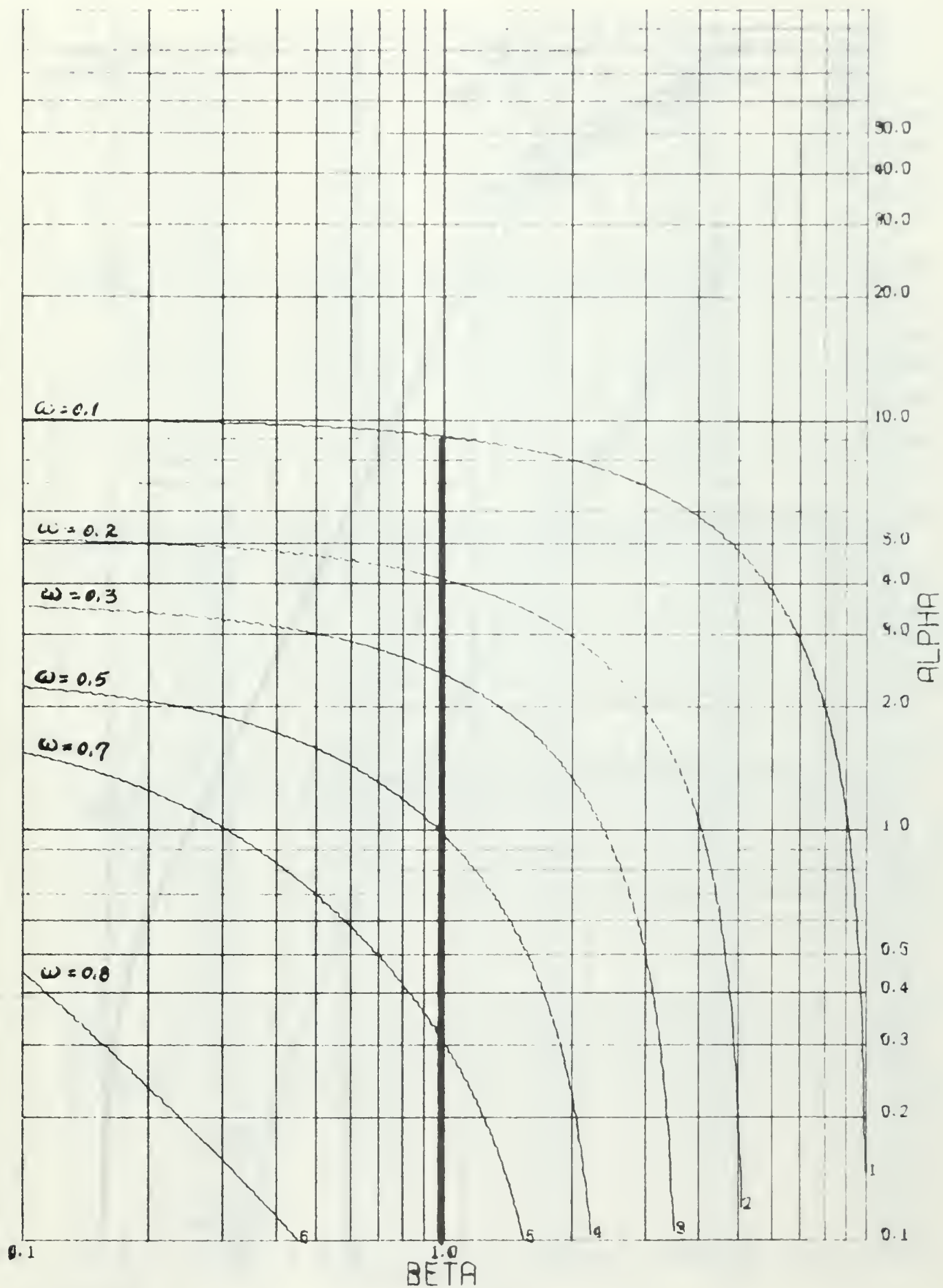


FIGURE 28.

R.A. NICHOLS, ALPHA(R1) VS BETA(R2), PARAM=OMEGA  
 2-LP SECT CASCADED, L=C=1.0, MAG(DB)=0.0



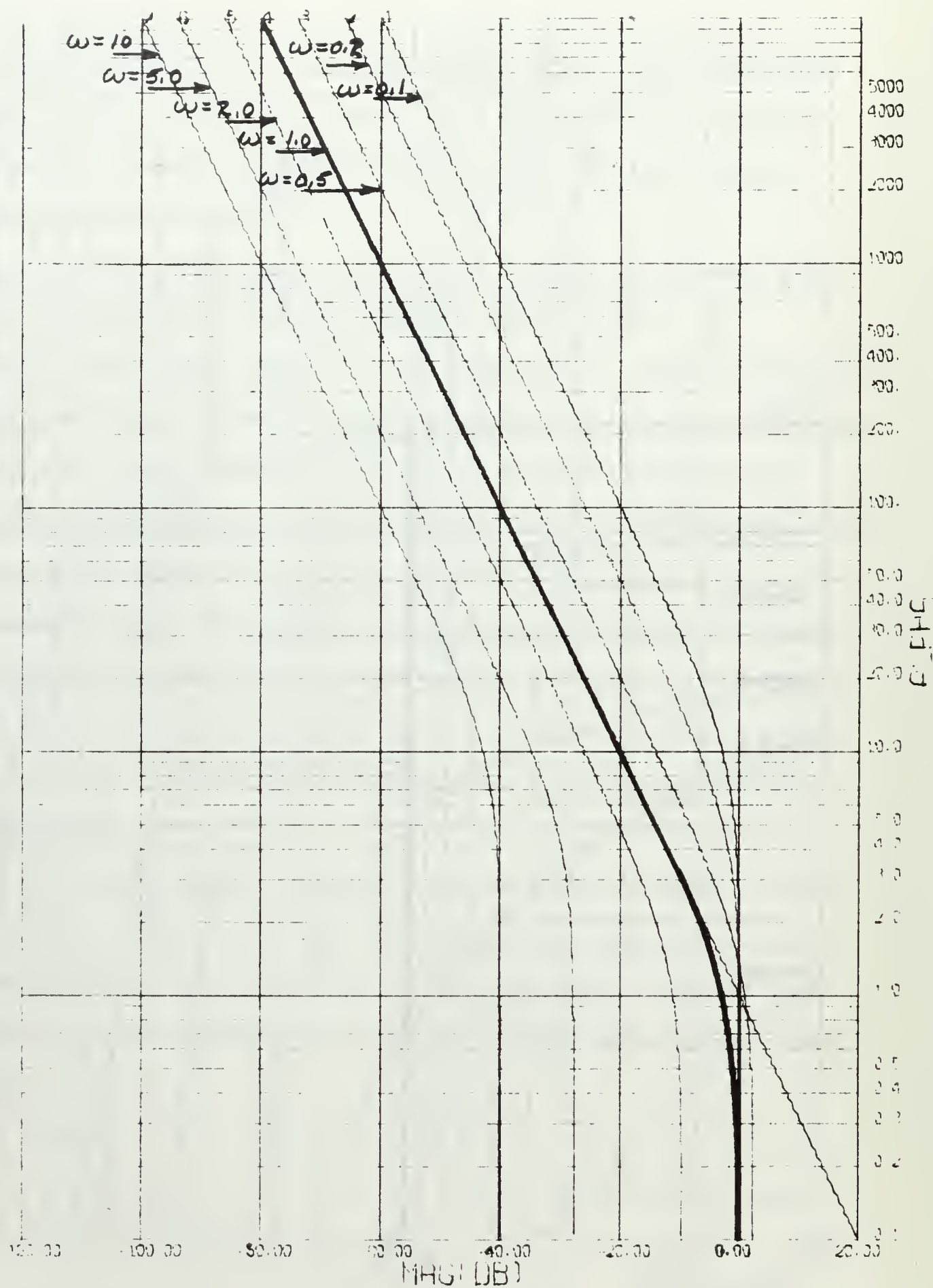


FIGURE 29.

R.A. NICHOLS, ALPHA(R1) VS MAG(DB), PARAM=OMEGA  
(E2 E1), 2-LP SECT CASCADED, L=C=1.0, R2=10000.0

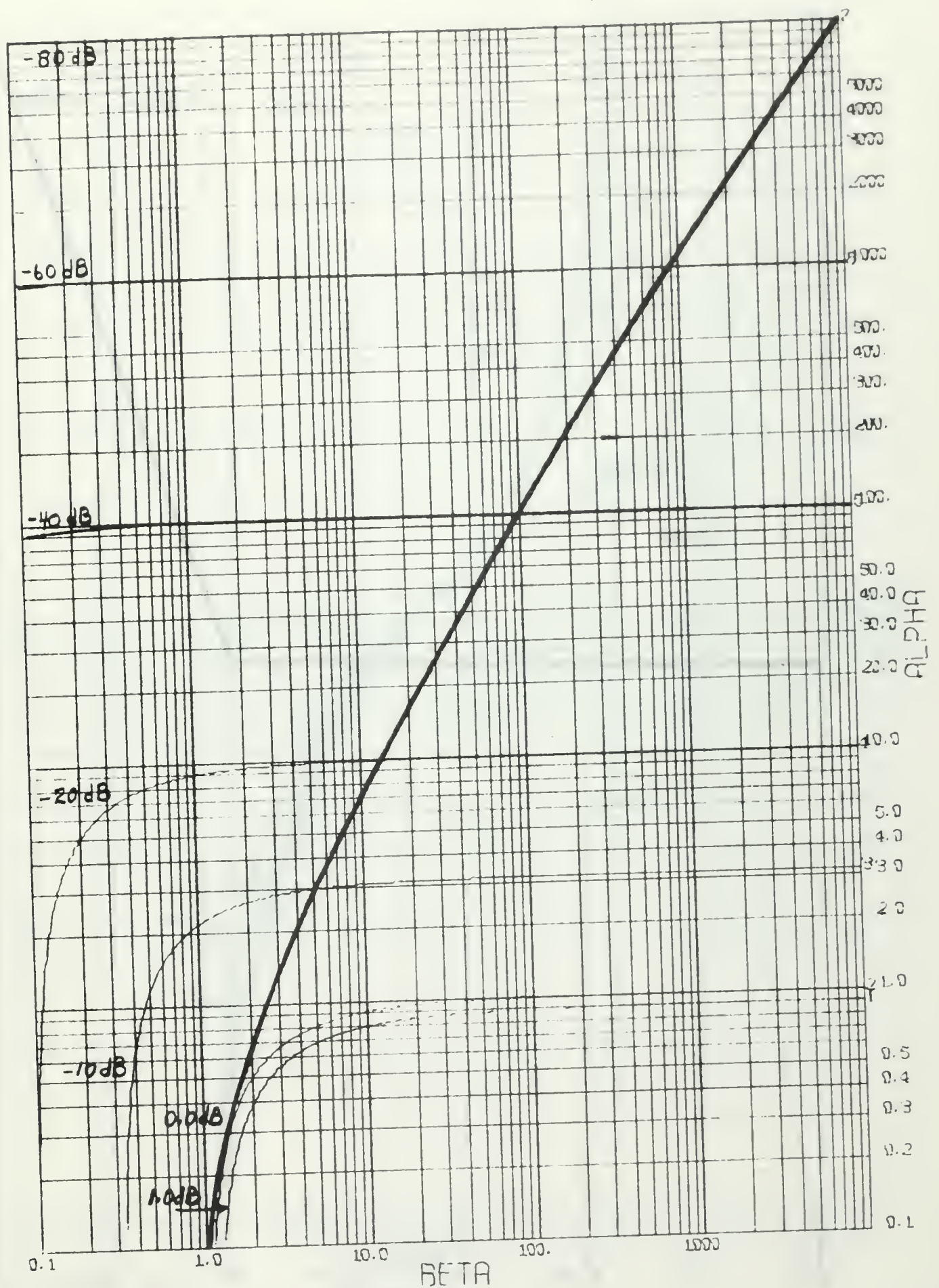


FIGURE 30.

R. A. NICHOLS,  $\alpha(\beta)$  VS  $\beta$ ,  $\text{PARAM} = \text{MAC}(\text{DB})$   
 $(E_2/E_1)$ , 2-LP SECT CASCADED,  $L=C=1.0$ ,  $\omega=1.0$ .

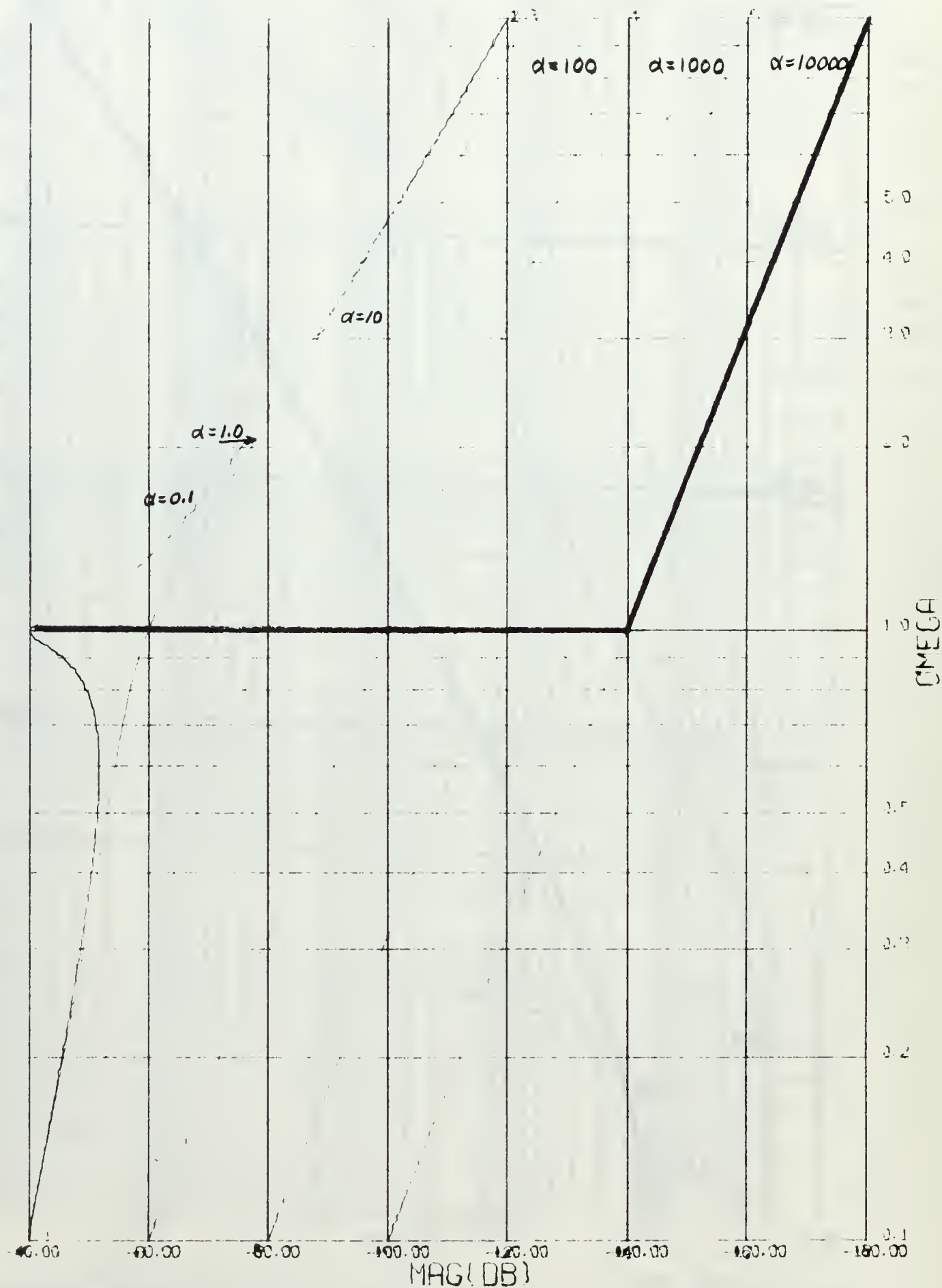


FIGURE 31.

R.A. NICHOLS, BODE PLOT, PARAMETER=BETA=R2  
(E3.E1), 2-LP SECT CASCADED, R1=1000.0, L-C=1.0



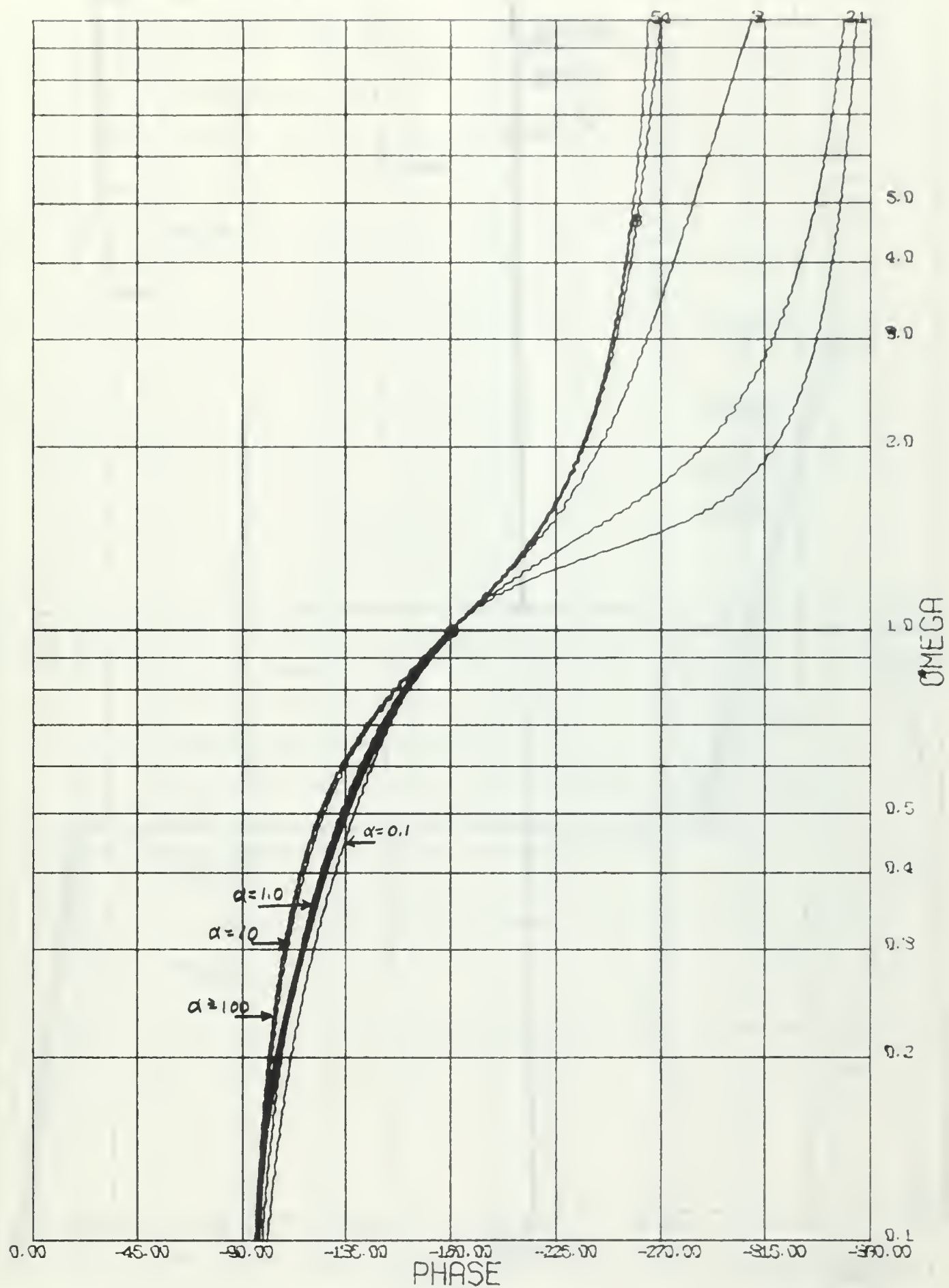


FIGURE 32.

R.A. NICHOLS, PHASE PLOT, PARAMETER=BETA=R2  
(E3/E1), 2-LP SECT CASCADED, R1=ALPHA=1.0=L=C



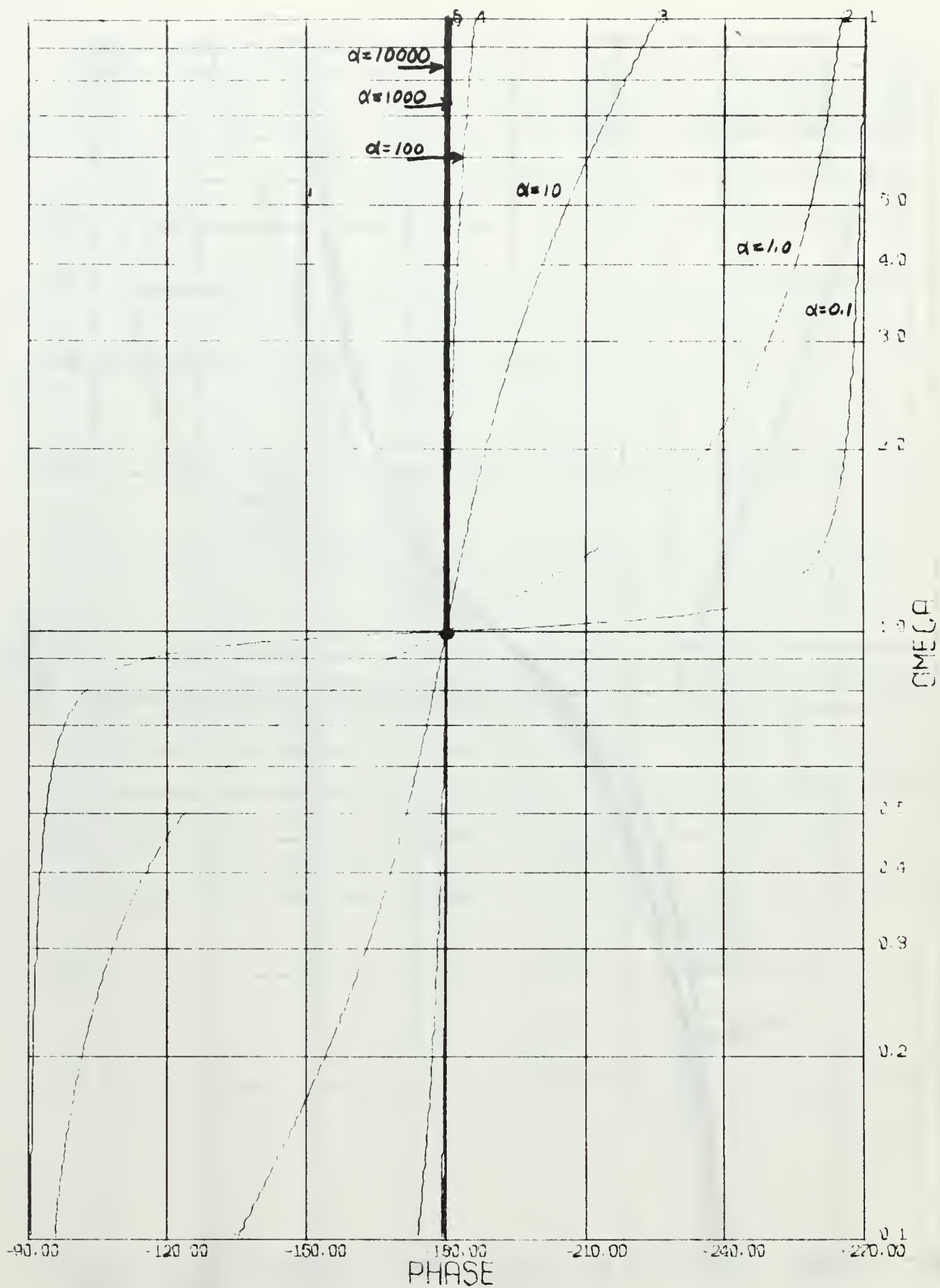


FIGURE 33.

R.A. NICHOLS, PHASE PLOT, PARAMETER=BETA=R2  
(E3/E1), 2-LP SECT CASCADED, R1=1000.0, L=C=1.0

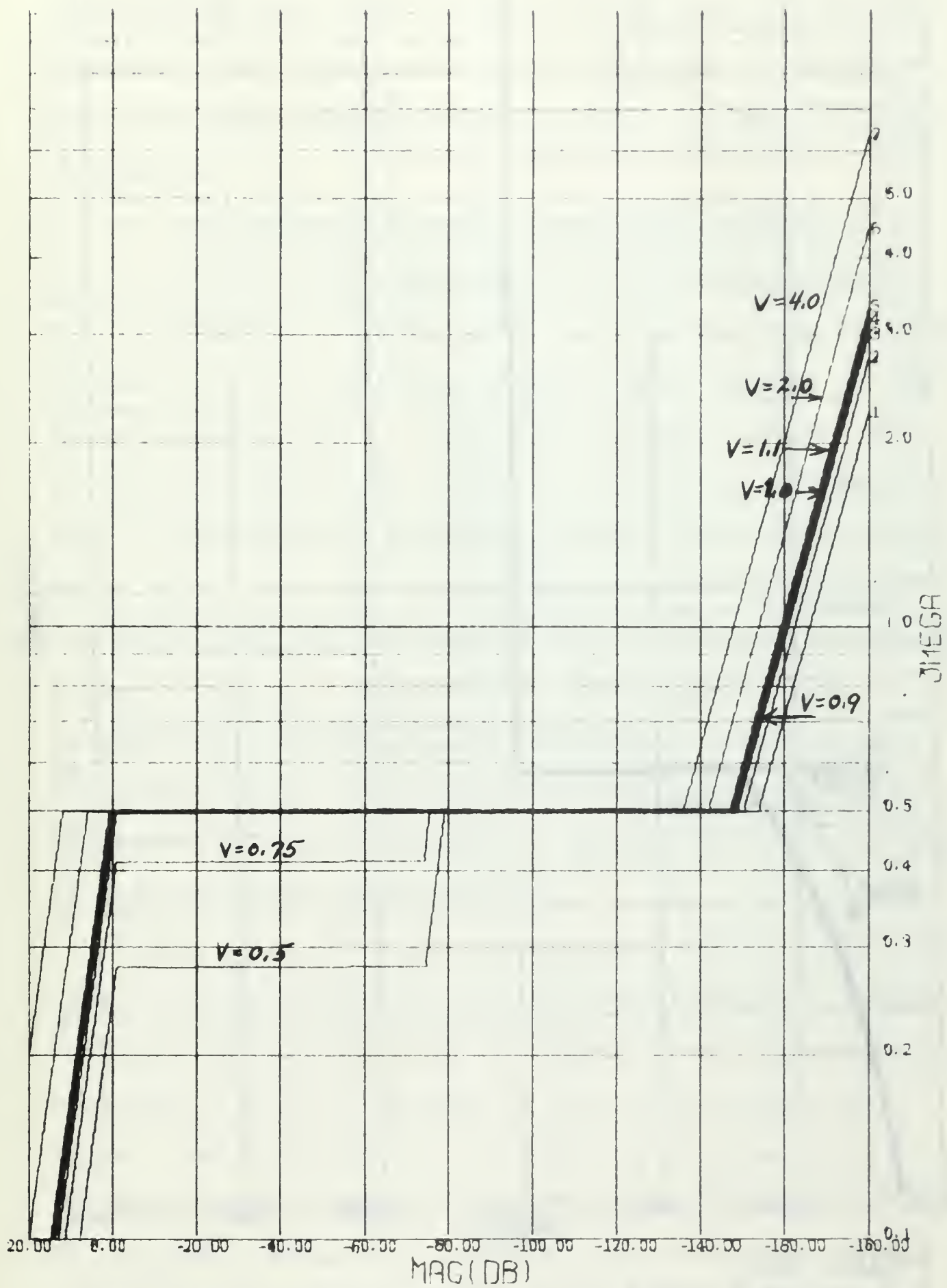


FIGURE 34.

R.A. NICHOLS, BODE PLOT, PARAM=(UINPUT\*1.0)  
 2-LP SECT CASCADED, TYPE 2, SIMULATION CHECK

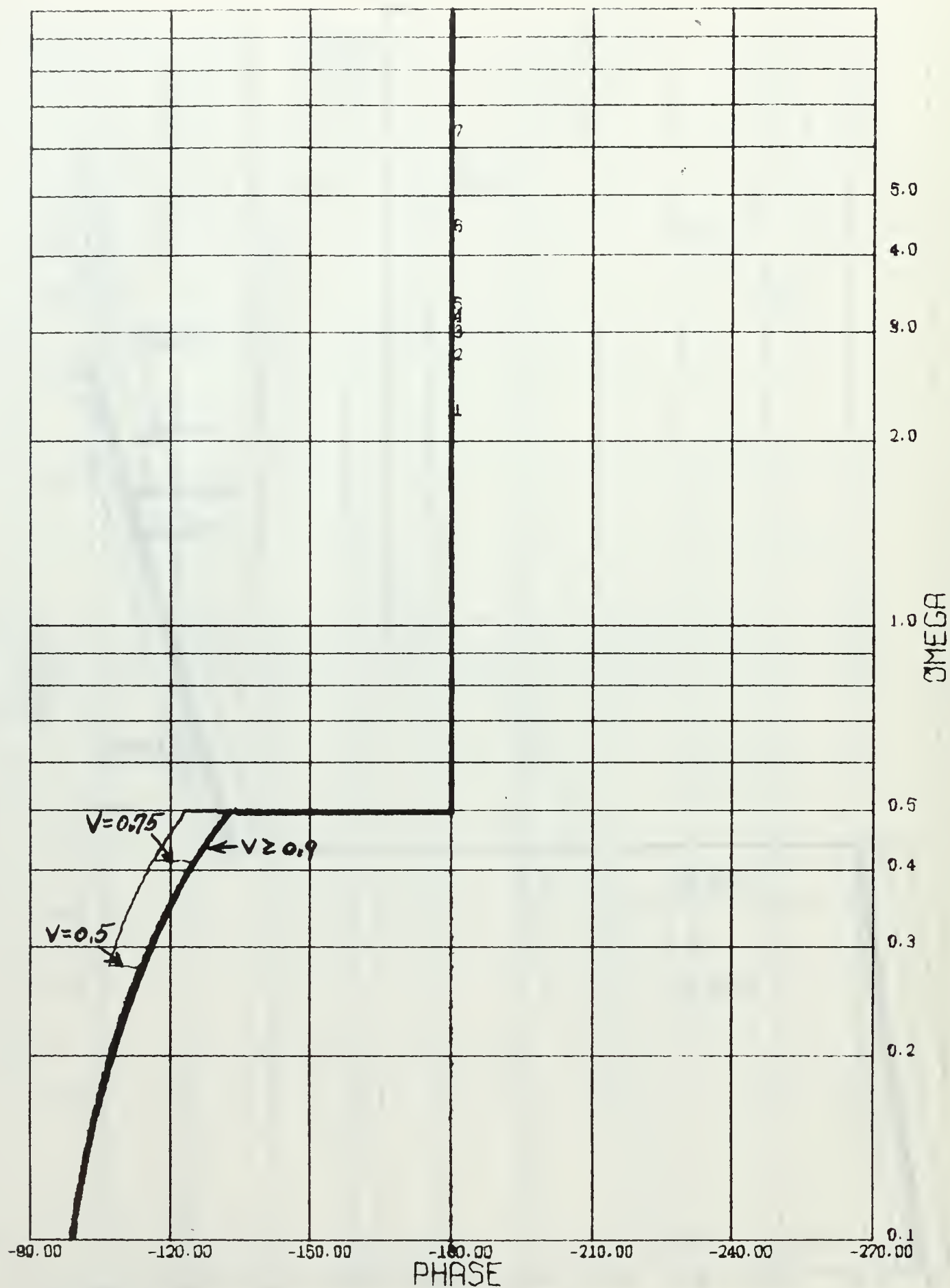


FIGURE 35.

R.A. NICHOLS, PHASE PLOT, PARAM=(VINPUT\*1.0)

2-LP SECT CASCADED, TYPE 2, SIMULATION CHECK

same as would have been obtained by concatenating the two sections. The concatenated filter is easier to realize than a type-two cascaded filter and has a greater stopband attenuation.

### 3. Two Nonlinear Elements in the Same Section

A third configuration for two nonlinear elements may be obtained by letting both the R and the C in the basic lowpass filter be nonlinear elements and functions of the filter transfer ratio. The design procedure is the same as that of the previous sections. Bode plots are made for each of the nonlinear elements with the other set to a best guess value. From the specifications and the Bode plot information minimum and maximum values for the elements are chosen to use in a design trial. The information is transferred to parameter-versus-magnitude plots and the nonlinear element characteristics determined. The interdependence of R and C requires a composite curve to be used in defining these characteristics.

Figure 36 is the alpha-versus-beta plot for omega equal to 1.0. Alpha represents the nonlinear R which is assumed to have a four-decade range of values. Beta represents the nonlinear C which is assumed to have a two-decade value range. The specifications are those of a lowpass filter. The heavy line in Figure 36 indicates the chosen alpha/beta relationship in the filter cutoff region. Figures 37 and 38 are the alpha- and beta-versus-magnitude plots with the element characteristic curves drawn in. Computer simulation



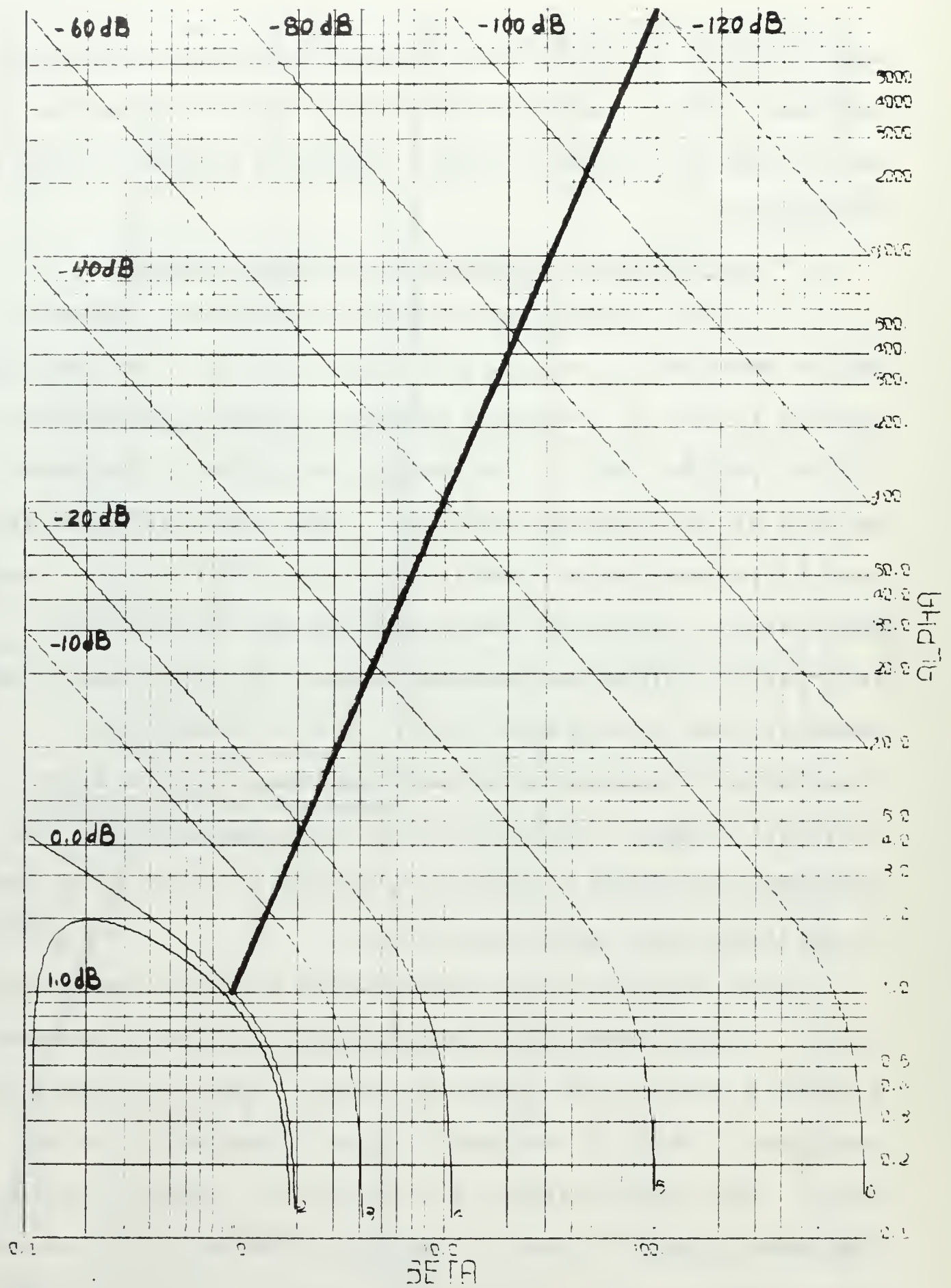


FIGURE 36.

R.A. NICHOLS. ALPHA VS BETA. PARAMETER=MAC (DB)  
LP FILTER. L=1.0. OMEGA=1.0. R=ALPHA. C=BETA

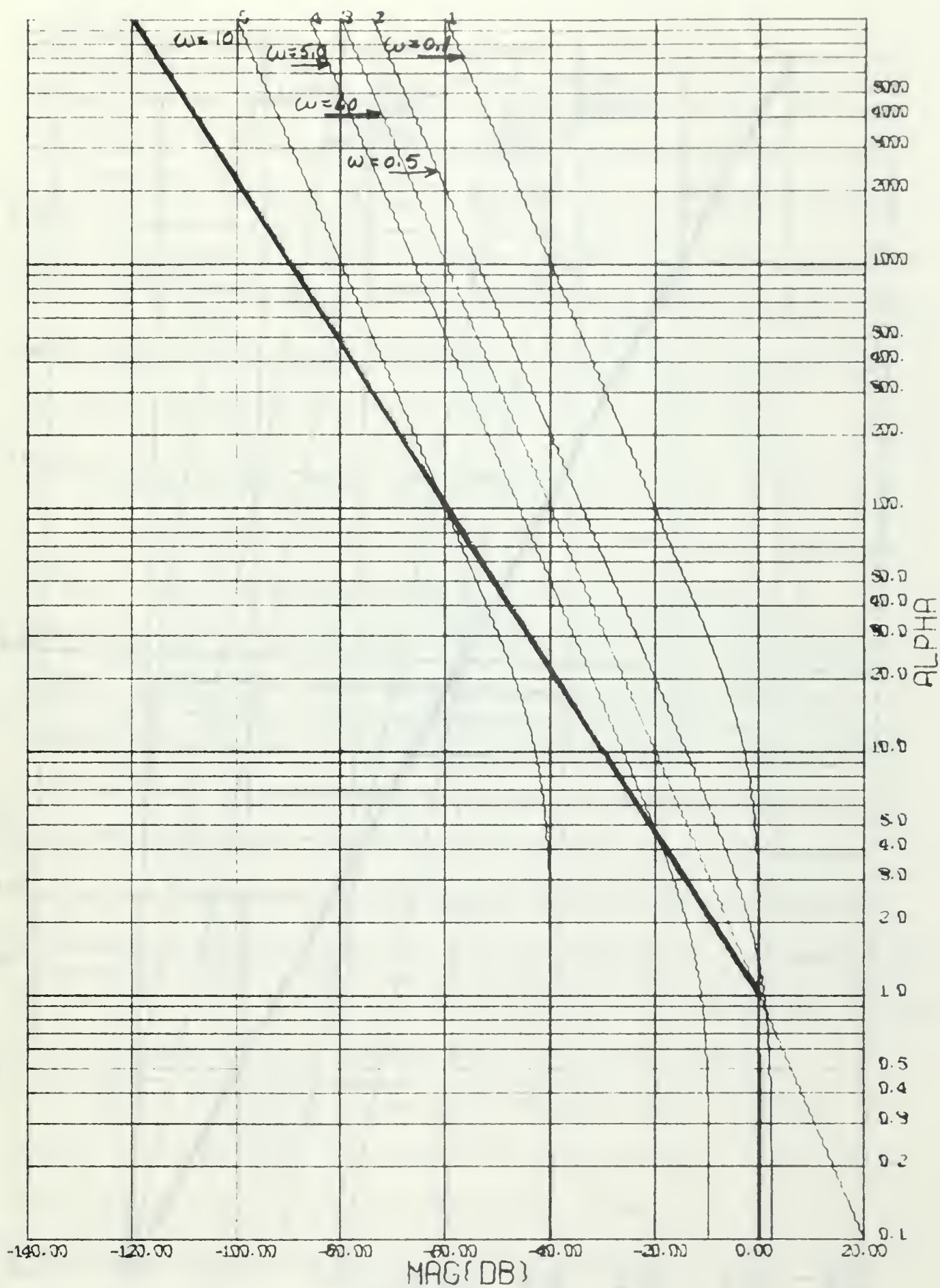


FIGURE 37.

R.A. NICHOLS, ALPHA US MAG (DB), PARAM=OMEGA  
LOWPASS FILTER, L=1.0, R=ALPHA, C=BETA=1.0

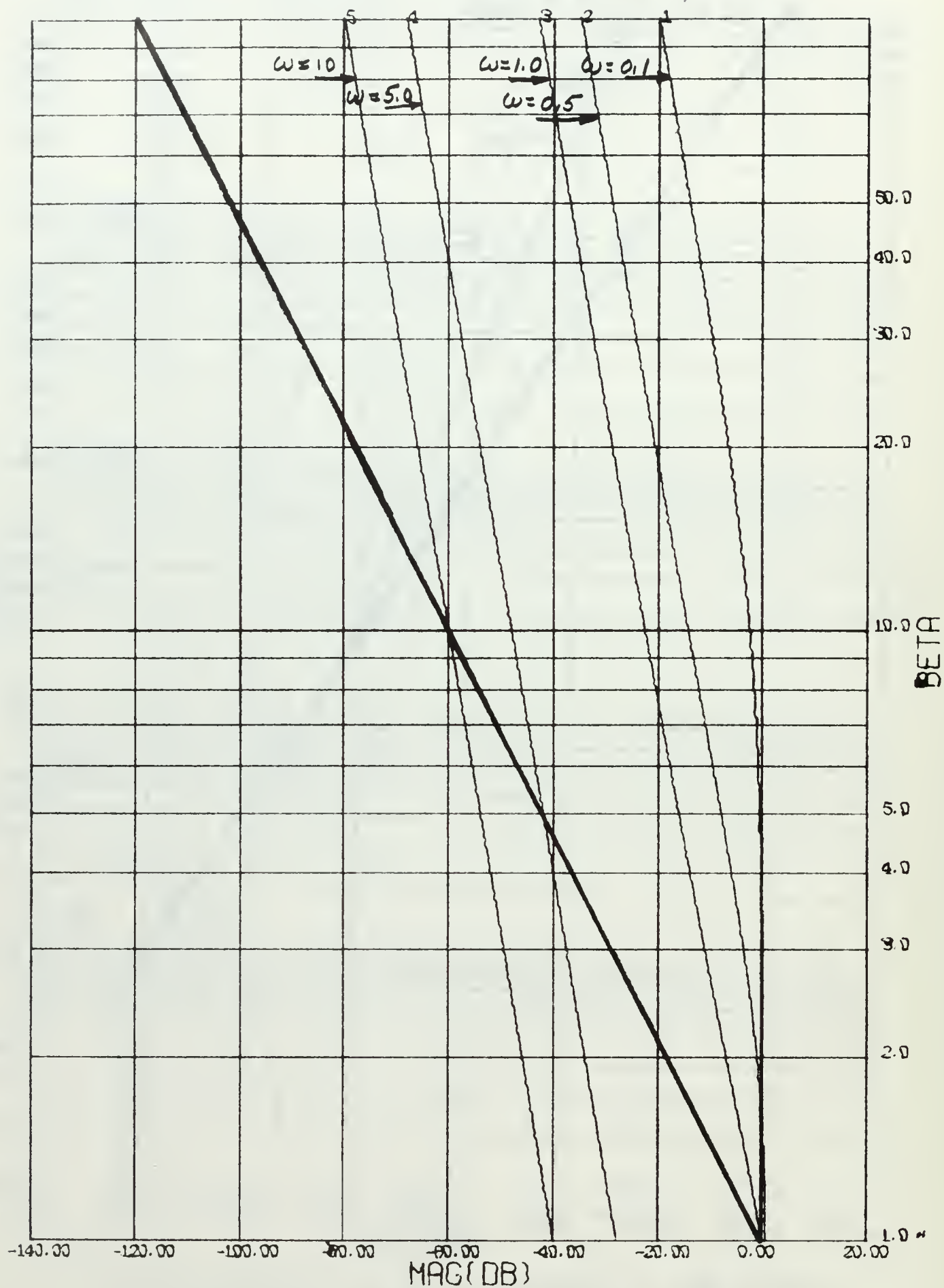


FIGURE 38.

R. A. NICHOLS, BETA VS MAG(DB), PARAMETER= $\omega$ MEGA  
 LOWPASS FILTER, L=1.0, R=ALPHA=1.0, C=BETA



results for this design are shown in Figure 39 for output magnitude and in Figure 40 for the phase. Alpha and beta are set to 1.0 when the output magnitude is greater than -1.0 dB and allowed to go to 10,000 and 100, respectively, when the magnitude drops below -1.0 dB. As before, the -1.0 dB level is used to represent a lag in changeover for the change initiation at 0.0 dB. The cutoff attenuation is 120.0 dB while the phase response is nonlinear.

### C. DESIGNING FOR PHASE RESPONSE

When the filter specifications concern phase response rather than output magnitude the desired response is drawn in on the phase plot rather than on the magnitude-versus-omega plot. The alpha-omega points are still transferred to the alpha-versus-magnitude plot for definition of the characteristics of the nonlinear element when it is a function of the filter output transfer function. Where the magnitude of the output is of interest the same alpha-omega points may also be transferred to the magnitude-versus-omega plot for an indication of the magnitude response corresponding to the filter phase specifications.

Figure 41 is the phase plot for the basic lowpass filter of Figure 3. The heavy line represents a specification calling for a linear 180-degree phase response between omega equal to 0.2 and 1.8. The alpha-versus-magnitude plot is shown in Figure 42. The magnitude characteristic



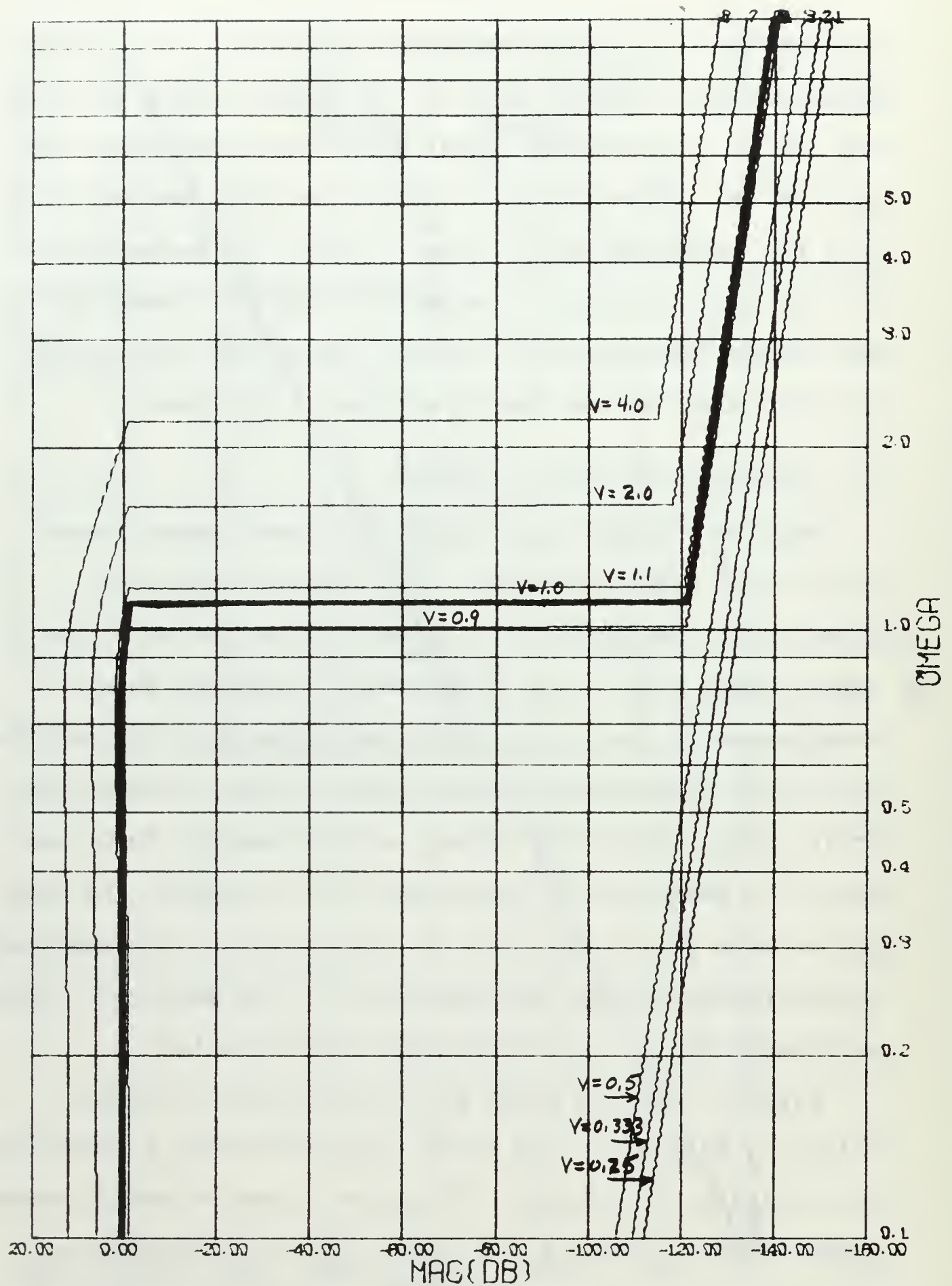


FIGURE 39.

R.A. NICHOLS, BODE PLOT, PARAM={UINPUT\*1.0}

LP FILTER SIMULATION CHECK, L=1.0, R=ALPHA, C=BETA

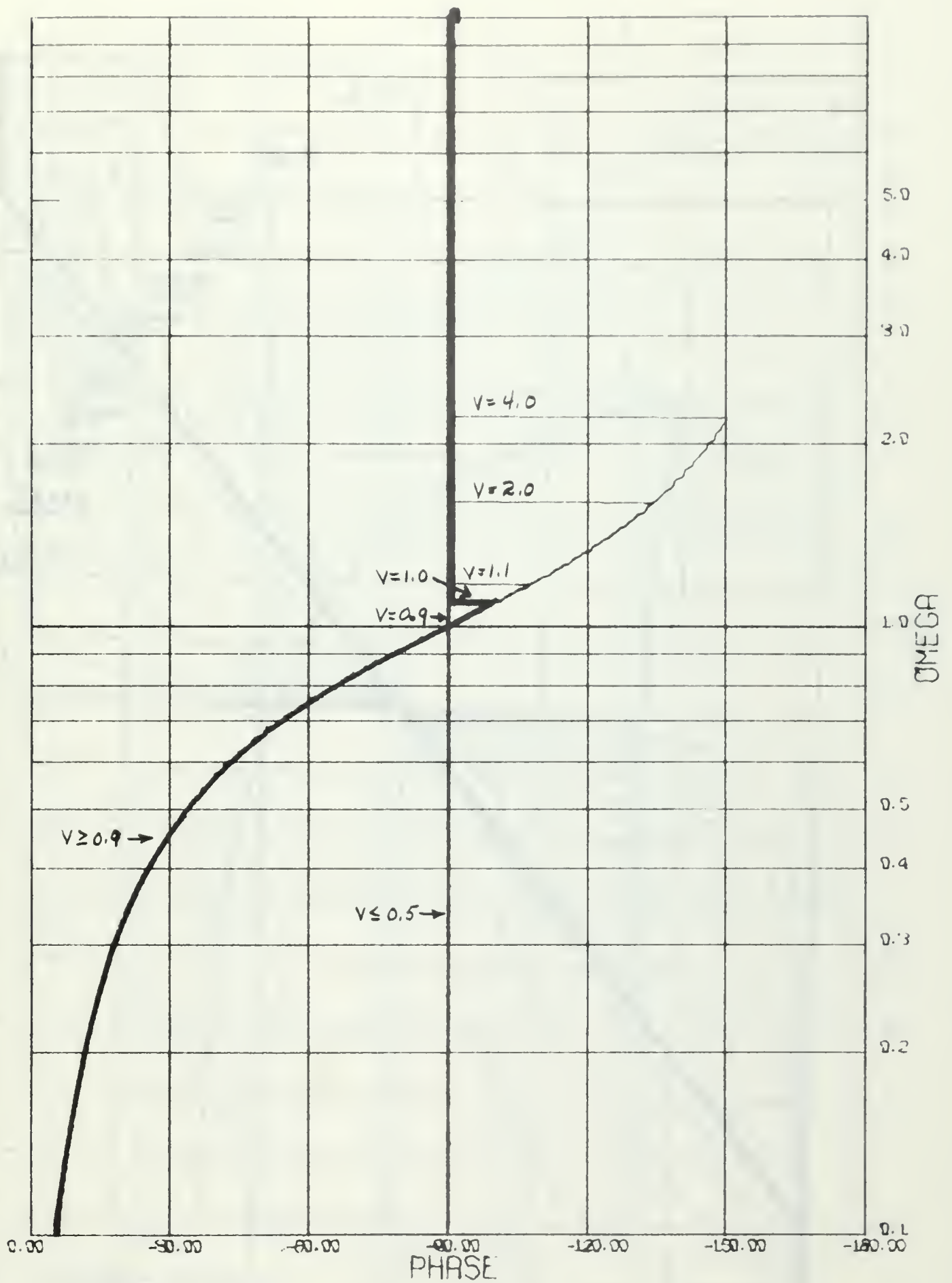


FIGURE 40.

R. A. NICHOLS, PHASE PLOT, PARAM=(UINPUT\*1.0)

LP FILTER SIMULATION CHECK, L=1.0, R=ALPHA, C=BETA

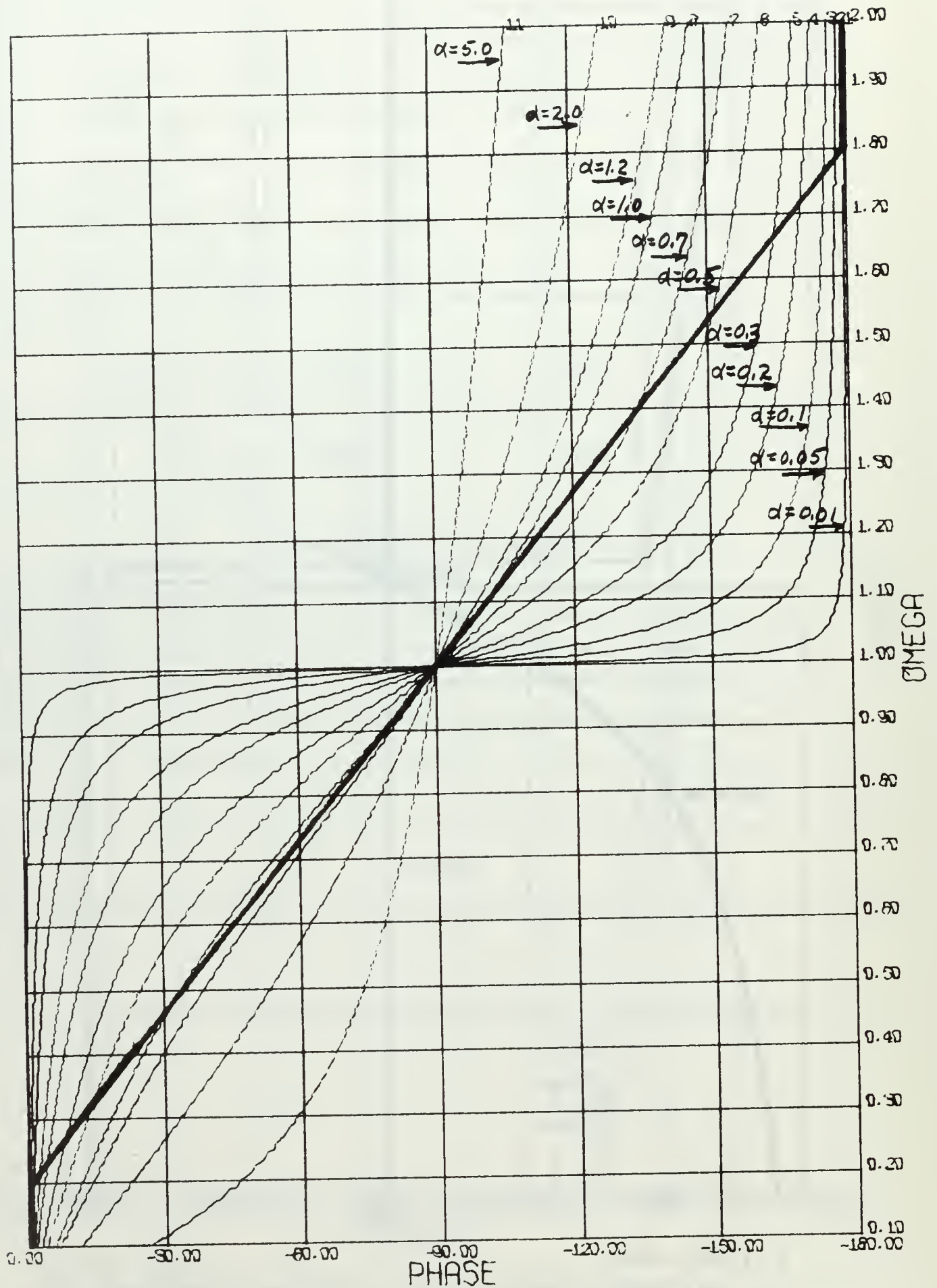


FIGURE 41.

R.A. NICHOLS, PHASE VS  $\Omega$ MEGA, PARAM=ALPHA=R  
 PHASE DESIGN WITH LOWPASS FILTER,  $L=C=1.0$

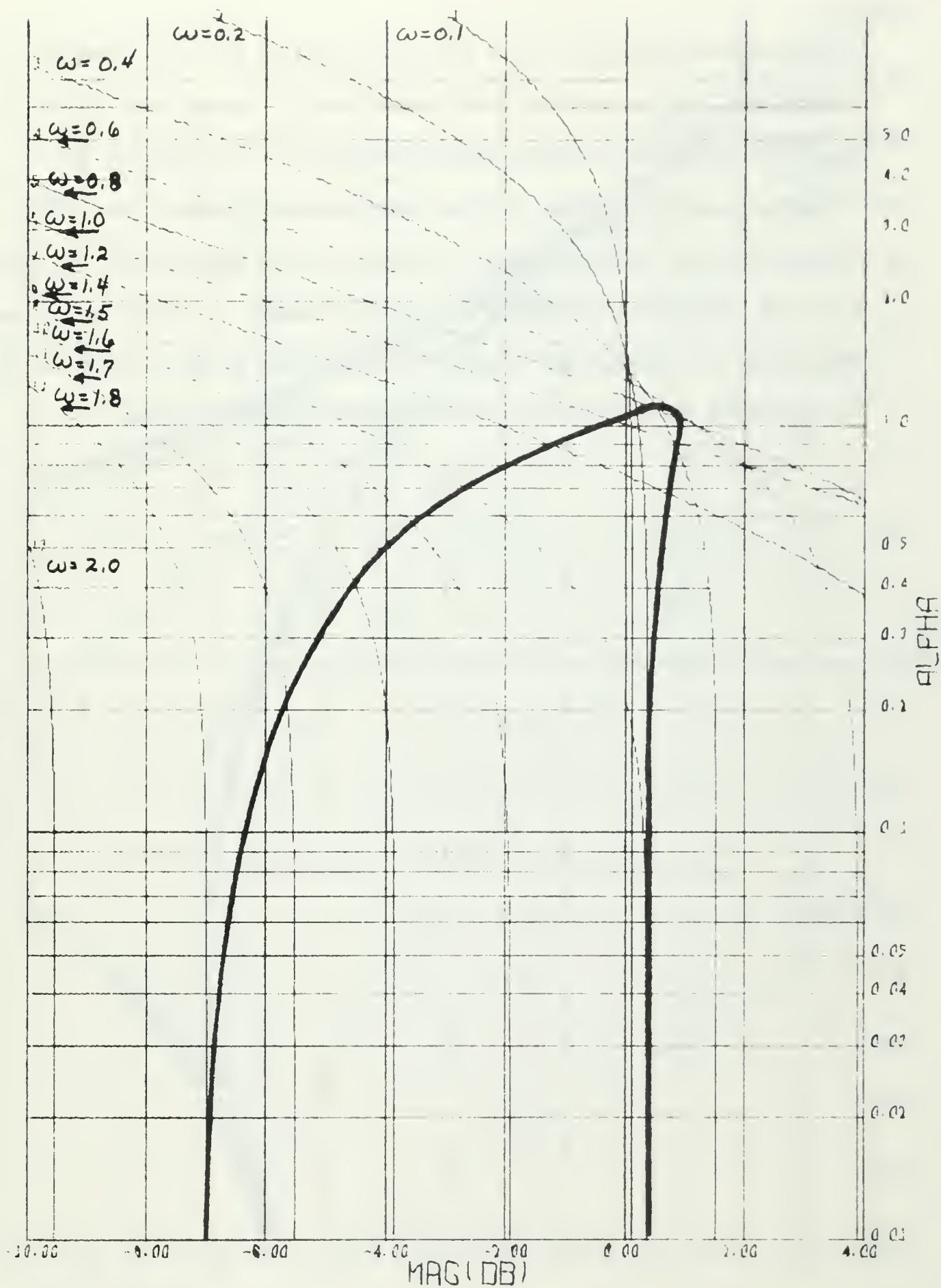


FIGURE 42.

R. A. NICHOLS, ALPHA(R) VS MAG (DB), PARAM=OMEGA  
 PHASE DESIGN WITH LOWPASS FILTER, L=C=1.0



$\alpha$  is fairly flat for the lower half of the frequency range but falls off in the upper half. This may also be seen in the magnitude-versus- $\omega$  plot of Figure 43.

The basic lowpass filter may be designed for a 180-degree linear phase shift if the output magnitude is not part of the specifications. If, however, a flat magnitude response is also important, the maximum phase shift would be limited to 90 degrees for this frequency range.

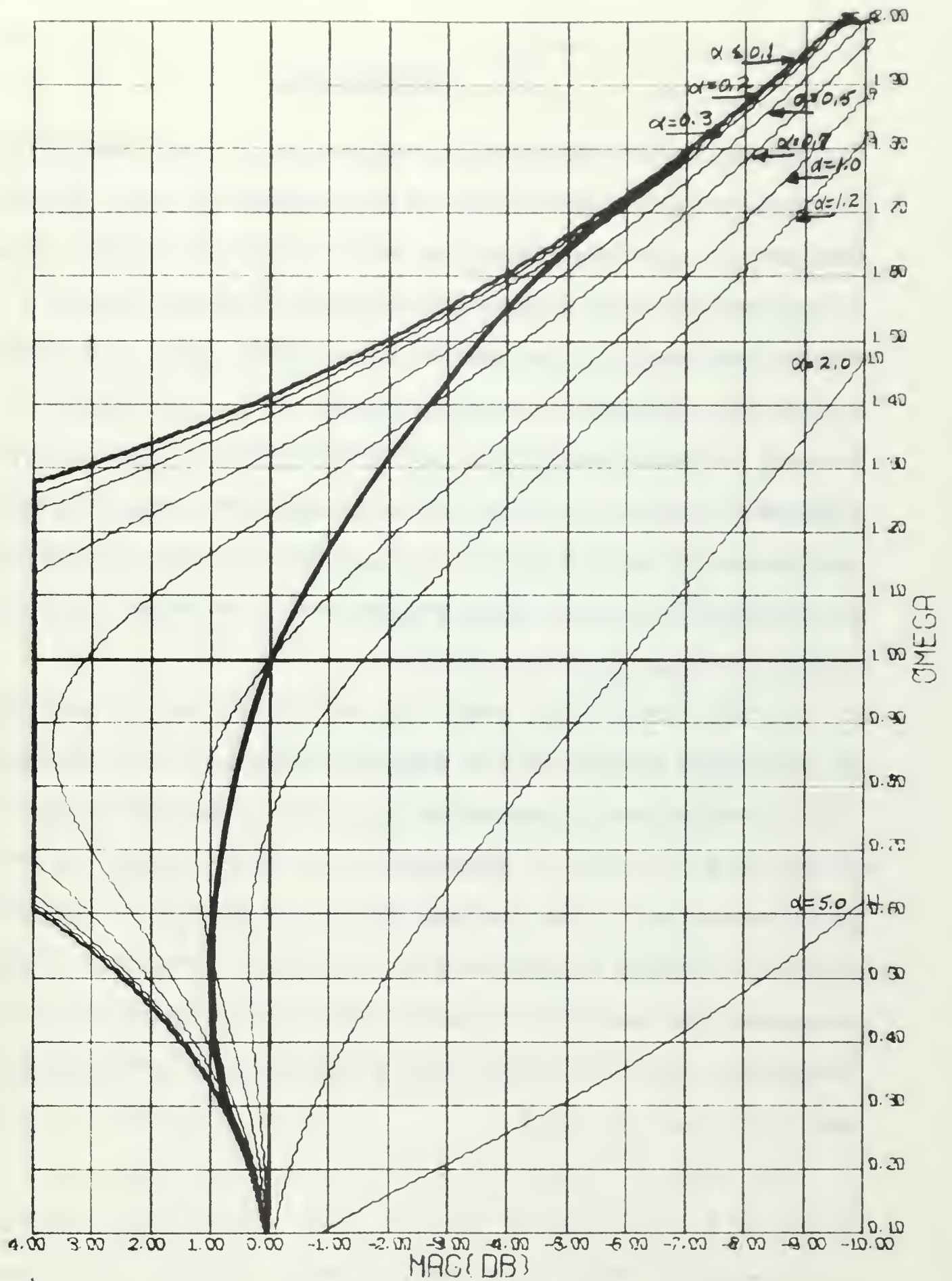


FIGURE 43.

R.A. NICHOLS, MAG(DB) VS OMEGA, PARAM=ALPHA=R  
 PHASE DESIGN WITH LOWPASS FILTER, L=C=1.0

#### IV. CONCLUSIONS

Filters with nonlinear elements may be designed using the frequency response form of the parameter plane method. The method is a graphical one which might be thought of as a counterpart to the describing-function method used in analytical design. Parameter-plane plots furnish the magnitude and frequency characteristics of the nonlinear element so that the filter may be designed to meet specifications. This method has the advantage of presenting the designer with a picture of the possible circuit conditions and thereby allowing value judgements to be made concerning the particular response chosen.

On the other hand, this form of filter design has the disadvantage common to all graphical methods. As the number of variables increases so does the number of graphs needed and the rate of growth of numbers of graphs is much faster than that for the number of variables. The point is finally reached where the number of graphs needed surpasses the ability of the designer to interpret and integrate them. At this point a hybrid form of graphical-analytics must be used.

The basic building block for filters with nonlinear elements is the lowpass filter. With a nonlinear  $R$  having a four-decade range of values, it will provide a stopband attenuation of 89 dB and a passband with a maximum rise of less than 1.5 dB. Adding a nonlinear  $L$  or  $C$  with a

two-decade range of values will increase the stopband attenuation to 120 dB. Multiple filter sections may be concatenated to reach even higher levels of attenuation. If the L and C elements are interchanged, the lowpass filter is transformed into a highpass filter. A bandpass filter may be formed by concatenating low- and highpass sections. The band-reject filter may be generated from the bandpass form. The lowpass filter may also be designed for a linear phase response. A linear 180-degree phase response is available for cases where a flat output magnitude is not necessary, or a linear 90-degree response where a reasonably flat output magnitude is specified.

Several areas exist for future investigation. The first one is that of the physical realization of these nonlinear filters, primarily the lowpass filter. Another is the investigation into the response of the filter to complex wave shapes. A third area is the extension of the method to include more complicated circuit configurations where the question of the optimum mix of nonlinear elements does not have an apparent answer. In addition, the use of feedback and feedforward paths should be investigated as response-shaping methods.



## APPENDIX A. COMPUTER PROGRAM INFORMATION

The two computer programs are written in the common FORTRAN IV language for use on the IBM-360 model 67 computer with a CALCOMP model 765 plotter for graphics. This is the installation at the Naval Postgraduate School. Documentation including data-card format information and internal section headings is written into each program. Both programs are capable of expansion beyond the present limitations of tenth-order transfer function and third-order alpha/beta parameters with 16 curves per graph and 900 points per curve. Linear, semi-log and log-log plots are available.

### 1. PARTF1 PROGRAM

PARTF1 provides graphs of alpha, beta, and omega (ordinate) versus magnitude (abscissa). Numerator and denominator polynomials in omega squared are formed from the s-domain transfer function and magnitude squared determined from their quotient. Graph points are generated by incrementing the desired ordinate parameter through the selected range of values while the other two parameters are held constant. The curve-family parameter is then set at the value for the next curve and the process repeated. Phase values are determined along with magnitude whenever the incremented parameter is omega. These phase values are available for plotting along the abscissa against omega.

Subroutines used with PARTF1 are GRPLOT, ABVAR and INTTFN. GRPLOT provides the plotting package for the program. The other two are used with the circuit simulation feature.

ABVAR is used to enter the FORTRAN statements describing the nonlinear parameter characteristics. Alpha and beta are initialized in the main program at each incrementation of omega, a solution made for magnitude and the information passed to this subroutine. The values of alpha, beta, magnitude and omega are then available for logic testing to determine the required alpha and beta values for that circuit condition. Flag KNR will cause a recycling of the magnitude solution using the new values of alpha and beta until the change in alpha is less than EPSA and in beta less than EPSB. KK1 is available as a loop counter. It is initialized whenever alpha and beta are initialized.

In cases where one of the parameters is not a function of the output transfer function, INTTFN is used. It is called by ABVAR when MDATA is set to one in the data set. The subroutine reads in additional data describing the internal transfer function and uses the ABVAR information to compute magnitude. This value, X2, is then passed back to ABVAR for use in determining parameter values.

The storage requirements of PARTF1 are set primarily by the "DIMENSION PHASE (16,901), YY(16,901)" card. The number "16" represents the maximum number of curve parameters or

voltage input values used while "901" is the maximum number of computation points plus one. Using these values, the program requires 205K plus 9K for the plotting package and about 19K for operations. This comes to about 233K. This may be reduced considerably by changing the statement to reflect the actual number required. For instance, if only six curves were to be plotted, the storage requirements would be reduced by about 72K ( $2 \times 10 \times 901 \times 4$ ). If only 500 points were used for each of the six curves, a further reduction in storage of about 19K would be gained.

As expected, the number of curves and plotting points also affects the run time. Compile time is about 23 seconds and the time for the link step about 1.5 seconds. A rough rule of thumb for go time is four seconds per 900-point curve. A six-curve run of 900 points per curve would have an execute time of around 48.5 seconds or about 50 seconds if a phase plot were also made.

Figure 44 is a repeat of Figure 6 using only 300 points per curve. Figure 45 uses only 100 points per curve. For design graphs of this size it would be wasteful in both storage and run time if 900 points per curve were demanded.

## 2. PARTF2 PROGRAM

PARTF2 provides graphs of alpha and beta versus omega, and alpha versus beta. As in the first program the input s-domain transfer function is separated into numerator and denominator functions which are individually transformed into the omega-squared domain. In PARTF2, however, the



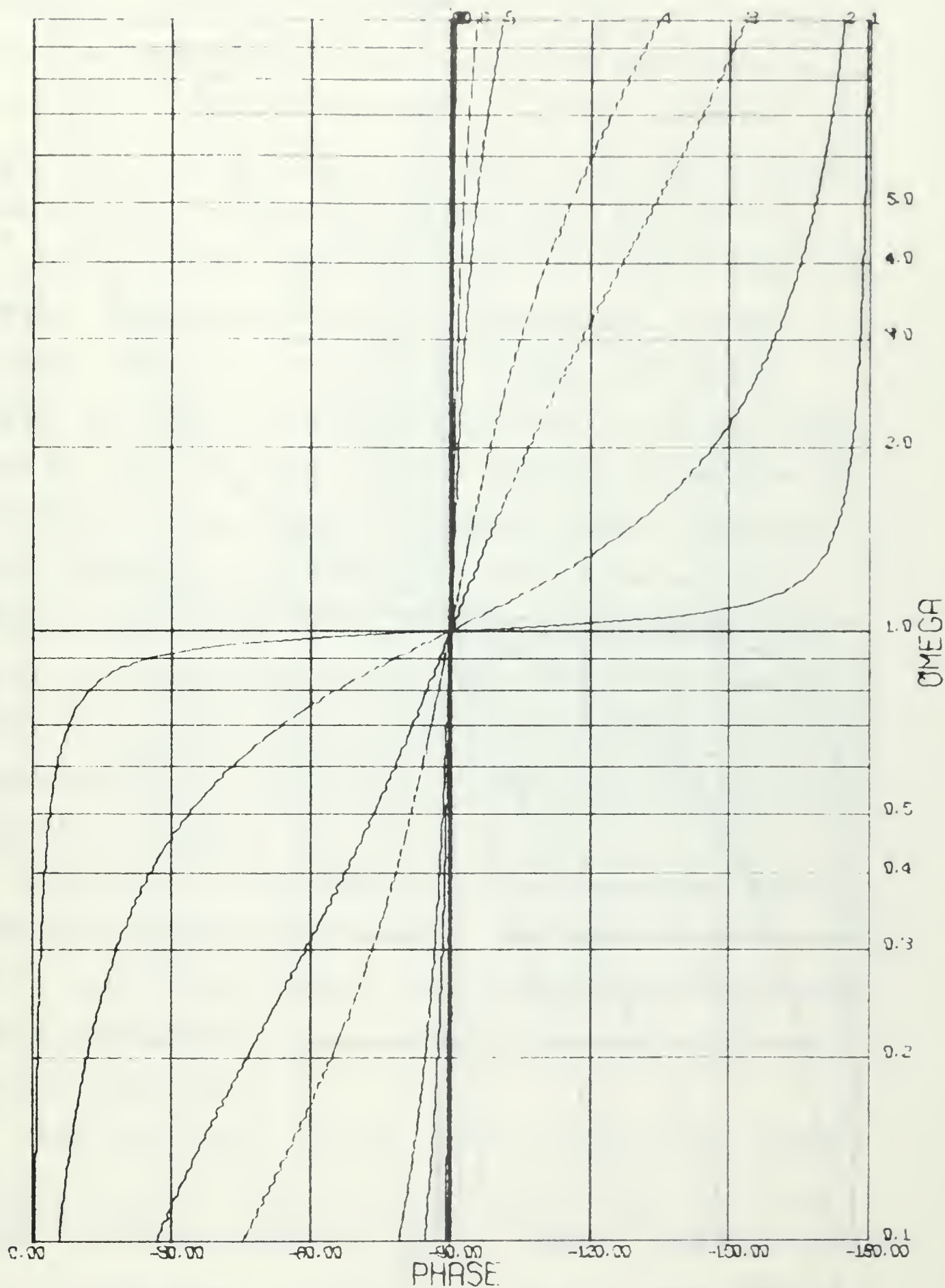


FIGURE 44.  
 R.A. NICHOLS, PHASE PLOT, PARAMETER=ALPHA  
 LOWPASS FILTER, L=C=1.0, NRPNTS=300



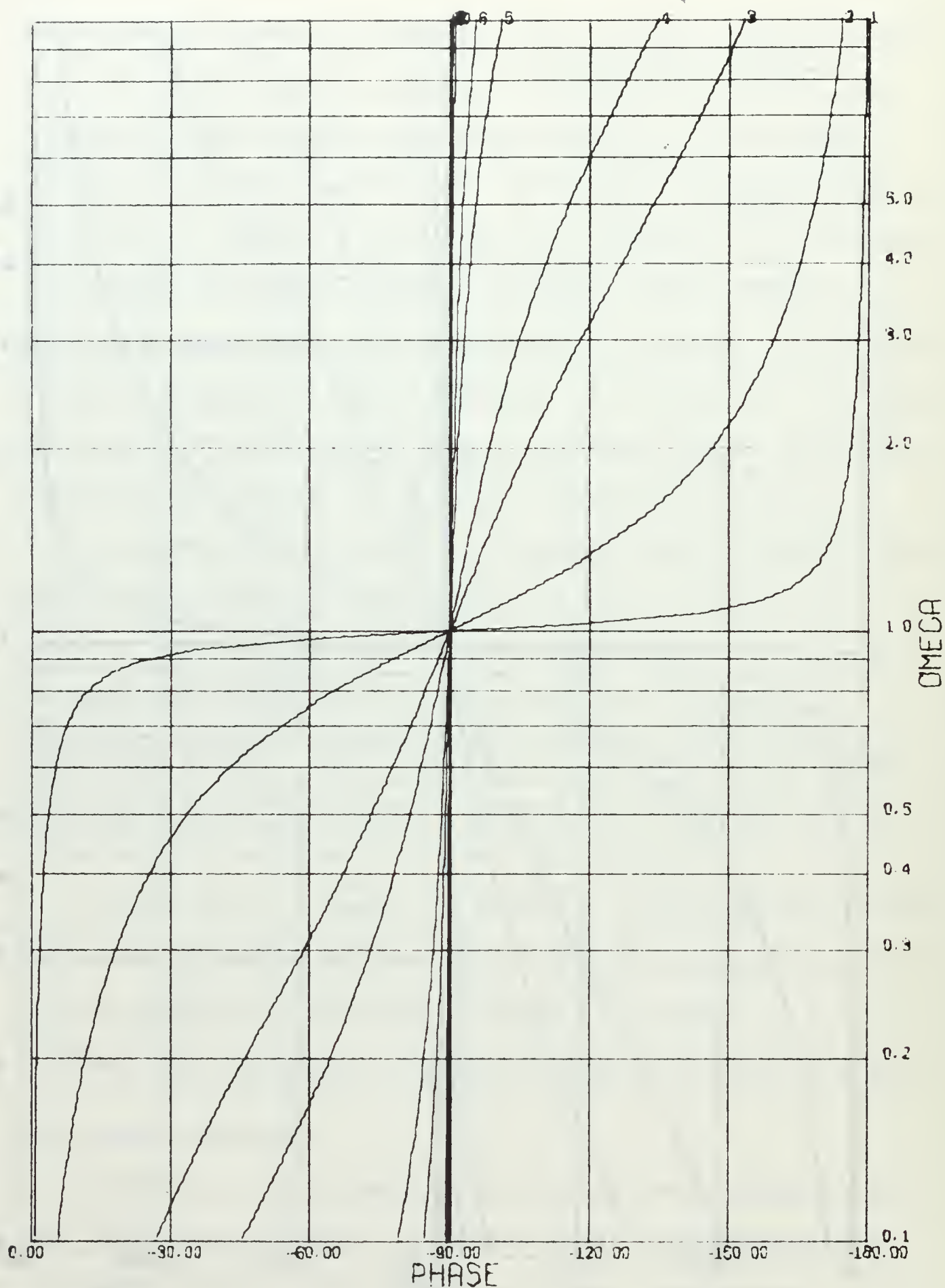


FIGURE 45.  
 R. A. NICHOLS, PHASE PLOT. PARAMETER=ALPHA  
 LOWPASS FILTER,  $L=C=1.0$ . NRPNTS=100

denominator is then multiplied by the square of the magnitude and subtracted from the numerator to form a single polynomial in terms of the unknown ordinate parameter. The real roots of this polynomial together with the incremented abscissa values generate the graph points for the curve.

The subroutines used with PARTF2 are GRPLOT, POLRT2 and POLRT3. GRPLOT provides the plotting package for the program. The other two are root-finding subroutines. POLRT2 is used when the polynomial order is two and POLRT3 when the order is three or more. Exponential overflow and underflow may occur in the high-order terms of the polynomial in POLRT3. This will not affect accuracy. The ERRSET command cancels the overflow and underflow error print order and prevents the program from being prematurely ended when a given number of them have occurred. POLRT3 is a modified POLRT routine from the IBM System/360 Scientific Subroutine Package.

Contrary to PARTF1 there is no one predominant factor setting the storage requirements. The limiting case of each factor contributes equally. Including the plotting package and operating space requirements, the storage requirement comes to about 148K.

PARTF2 run times are much longer than those for PARTF1. Forming the polynomial, solving for the roots, selecting roots, etc. multiplies the run time over that for the simple quotient procedure of PARTF1 by a factor of seven. The go

time rule of thumb is 28 seconds per 900-point curve. The compile, link and edit time is about 23 seconds. Thus the estimated run time for eight 900-point curves would be about 247 seconds ( $8 \times 28 + 23$ ). It pays to use fewer curves and fewer points with PARTF2.

[illegible][illegible]

SYMBOL 11545E

NUMBER OF RUNS DESTROYED. EACH PIN MUST HAVE A FULL SET OF DATA CARDS.

### Plot Number (Y-Axis vs X-Axis)

1=ALPHA VS MAGNITUDE, BETA FIXED, OMEGA PARAMETER.  
2=ALPHA VS MAGNITUDE, ALPHA FIXED, OMEGA PARAMETER.  
3=OMEGA VS MAGNITUDE, BETA FIXED, ALPHA PARAMETER.  
4=OMEGA VS MAGNITUDE, ALPHA FIXED, BETA PARAMETER.  
5=OMEGA VS MAGNITUDE, ALPHA AND/OR BETA FUNCTIONS.  
OF OUTPUT MAGNITUDE IS AVAILABLE WITH PLOTR 3, 4, 5.  
PHASE VS MAGNITUDE IS AVAILABLE WITH PLOTR 3, 4, 5.

(NOTE: NCBNUJN NCBNUJN NCBNUJN)

ON PHASE(16,901), YY(16,901) CARD MAY BE CHANGED  
TO REDUCE THE STORAGE REQUIRED. THE FIRST NUMBER  
MUST BE .6E. NDCURV.

NR.DATS.

I WRITE

NV:APT

# GRAPH

GRAPH ORDER.  
-1= NO GRAPHS DESIRED.



TE1041  
TE1042  
TE1043  
TE1044  
TE1045  
TE1046  
TE1047  
TE1048  
TE1049  
TE1050  
TE1051  
TE1052  
TE1053  
TE1054  
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TE1065  
TE1066  
TE1067  
TE1068  
TE1069  
TE1070  
TE1071  
TE1072  
TE1073  
TE1074  
TE1075  
TE1076  
TE1077  
TE1078  
TE1079  
TE1080  
TE1081  
TE1082  
TE1083  
TE1084  
TE1085  
TE1086  
TE1087  
TE1088

0 = GRAPHS ARE DESIRED.  
1 = GRAPH OF PHASE VS OMEGA DESIRED. USED WITH  
PLOTNR 3, 4, 5.  
ALPHA SCALE CODE. USED WITH PLOTNR 1.  
0 = LOG SCALE.  
1 = LINEAR SCALE.  
BETA OUTPUT AXIS SCALE CODE. USED WITH PLOTNR 2.  
0 = LOG SCALE.  
1 = LINEAR SCALE.  
MAGMIN, MAGMAX AND MAGNITUDE OUTPUT SCALE CODE.  
0 = DR. VALUES.  
1 = ACTUAL VALUES.  
2 = SQUARED VALUES.  
OMEGA OUTPUT AXIS SCALE CODE. USED WITH PLOTNR 3,  
4, 5.  
0 = LOG SCALE.  
1 = LINEAR SCALE.  
SURROUTINE INTEN ACTIVATION. USED WITH PLOTNR  
5 WHEN PARAMETER IS A FUNCTION OF AN INTERNAL  
TRANSFER FUNCTION. SEE THE SUBROUTINE FOR DETAILS  
HEIGHT OF THE VERTICAL AXIS, Y-AXIS, OF THE GRAPH  
IN INCHES. FOR TOTAL PAGE HEIGHT ADD 1.0 INCHES  
FOR GRAPH SCALES, AXIS LABEL AND GRAPH TITLING.  
WIDTH OF THE HORIZONTAL AXIS, X-AXIS, OF THE  
GRAPH IN INCHES. FOR TOTAL PAGE WIDTH ADD 0.5  
INCHES FOR GRAPHS, SCALES AND AXIS LABEL. TOTAL  
WIDTH IS LIMITED BY PAGE SIZE, USUALLY 8.0 INCHES  
NUMBER OF UNITS PER LINE ON THE VERTICAL SCALE.  
IF SET=0, IT WILL BE SCALED AUTOMATICALLY TO  
(YMAX-YMIN)/YHIG. IT IS NOT USED WITH LOG SCALES.  
NUMBER OF UNITS PER LINE ON THE HORIZONTAL SCALE.  
IF SET=0, IT WILL BE SCALED AUTOMATICALLY TO  
(XMAX-XMIN)/XWID. IT IS NOT USED WITH LOG SCALES.  
MINIMUM VALUE FOR PHASE. ALL PHASE VALUES ARE  
CONSIDERED NEGATIVE (-360.0 DE. PHASE .LE. 0.0).  
IF SET=0, PHSMIN=-360.0.  
MAXIMUM VALUE FOR PHASE.  
NUMBER OF DEGREES PER SCALE MARKING. IF SET=0,  
IT WILL BE AUTOMATICALLY SCALED TO 45.0 DEGREES  
PER LINE.  
MINIMUM VALUE FOR ALPHA.  
ALPMA X  
MAXIMUM VALUE FOR ALPHA.  
ALPMA X  
MINIMUM VALUE FOR BETA.  
BETMA X  
MAXIMUM VALUE FOR BETA.  
BETMA X  
MINIMUM VALUE FOR MAGNITUDE. SEE MAGSCL.  
MAGMA X

CC

TE110090  
TE110091  
TE110092  
TE110093  
TE110094  
TE110095  
TE110096  
TE110097  
TE110098  
TE110099  
TE110100  
TE110101  
TE110102  
TE110103  
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TE110134  
TE110135

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CMGMIN  MINIMUM VALUE FOR OMEGA.
CMGMAX  MAXIMUM VALUE FOR OMEGA.
NOTE: IF AXIS SCALE CODE IS LOG, MIN.GE.0.001, MAX.LE.10000.0.

6  RE10.3  SETALP  VALUE OF ALPHA WHEN USED AS A CONSTANT.
    SETRET  VALUE OF BETA WHEN USED AS A CONSTANT.
            (USED AS INITIAL ALPHA/BETA VALUES WHEN PLOTNR=5)

7  RE10.3  VINUT   VOLTAGE INPUT VALUES (VINUT#1.0) USED WITH
    PLOTNR 3,4,5. OMIT IF PLOTNR=1,2 OR NVINPT=0.
    USE TWO CARDS IF NVINPT .GT. 9.

8  RE10.3  CURPAR  CURVE PARAMETER VALUES. USE TWO CARDS IF NDCURV
    .GT.9. OMIT IF PLOTNR=5.

9  RE10.3  AN      NUMERATOR COEFFICIENTS IN ASCENDING ORDER OF THE S
    S EXPONENTS. TWO CARDS ARE USED FOR EACH OF THE S
    EXPONENTS FROM S**0 THROUGH THE POLYNOMIAL ORDER.
    (1)  *1.0,  *R,  *R**2,  *R**3,  *R**3,
        *A,  *A**R,  *A**R**2,  *A**R**3,
        *A**2,  *A**2**R,  *A**2**R**2,  *A**2**R**3,
        *A**3,  *A**3**R,  *A**3**R**2,  *A**3**R**3.

10 RE10.3  AP      DENOMINATOR COEFFICIENTS IN ASCENDING ORDER OF THE S
    S EXPONENTS. TWO CARDS ARE USED FOR EACH OF THE S
    EXPONENTS FROM S**0 THROUGH THE POLYNOMIAL ORDER.
    SAME FORMAT AS CARD NUMBER 9 (NUMERATOR COEFF).

11 14A4  GTITL1  GRAPH TITLE LINE NUMBER ONE.
12 14A4  GTITL2  GRAPH TITLE LINE NUMBER TWO.
13 14A4  GTITL3  GRAPH TITLE LINE NUMBER THREE.
14 14A4  GTITL4  PHASE GRAPH TITLE LINE NUMBER ONE.
15 14A4  GTITL5  PHASE GRAPH TITLE LINE NUMBER TWO.
16 14A4  GTITL6  PHASE GRAPH TITLE LINE NUMBER THREE.

NOTE: OMIT CARDS 11-16 IF IGRAPH=-1. OMIT CARDS 13-16 IF IGRAPH=0.

***** PROGRAM FOLLOWS *****
INTEGER PLOTNR,ALPSC,RETSC,CMGSC,7SCALE
REAL MAGMAX,MAGMIN
DIMENSION A(11),C(11),CN(11),PAN(11),PAD(11)
DIMENSION CURPAR(16),VINUT(16)

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15 DIMENSION GTITL1(14),GTITL2(14),GTITL3(14),GTITL4(14),GTITL5(14),
16 GTITL6(14)
17 * DIMENSION ALPHA(901),PHSDEG(901),ZVAL(901)
18 * DIMENSION MAXIP(901),PHTA(901),XMAX(901),DMEGA(901),X(901),Y(901),
19 * DIMENSION AA(11,16),AD(11,16),AN(11,16)
20 * DIMENSION PHASE(16,901),YY(15,901)
21 * DIMENSION MAGSCL,MARVAR,EPLOG,KNR,KK1,MDATA,GTITL5
22 * COMMON GTITL1,GTITL2,GTITL3,GTITL4,GTITL5,GTITL6,XSCALE,YSCALE,ZLOGMN
23 * COMMON XMAX,XMIN,ZMAX,ZMIN,MSCALE,XSCALE,YSCALE,YHIGH,PLPNTNR,IC,IP
24 * COMMON X,Y,XUPL,XWIDE,YWIDE,YHIGH,PLPNTNR,IC,IP
25 * FORMAT(1H1)
26 * FORMAT(14A4)
27 * FORMAT(10X,14A4)
28 * FORMAT(10X,14A4)
29 * FORMAT(8I10)
30 * FORMAT(10X,8I10)
31 * FORMAT(8E10.3)
32 * FORMAT(10X,1P8E12.3)
33 C***** READ IN DATA *****
34 READ(5,7) NRUN
35 IPUN=1
36 * READ(5,7) PLGTNR,NORNJM,NORDEN,NPCURV,NRPNTS,IWRITE,NVINPT
37 * NPPI=NCRDEN+1
38 * IF(NRPNTS.EQ.0) NRPNTS=900
39 * NRPTM1=NRPNTS-1
40 * IPNR=1
41 * EPLOG=1,OF=50
42 * READ(5,7) IGRAPH,ALPSCS,BETSCL,MAGSCL,DMGSCL,MDATA
43 * MARVAR=1
44 * READ(5,9) YHIGH,XWIDE,YUPL,XUPL,PHSMIN,PHSMAX,PHSUPL
45 * READ(5,9) ALPMIN,ALPMAX,RETMIN,RETMAX,MAGMIN,MAGMAX,DMGMIN,DMGMAX
46 * IF((PLGTNR.EQ.3).OR.(YUPL.NE.0.0)) GO TO 20
47 * IF((PLGTNR.EQ.1) YUPL=(ALPMAX-ALPMIN)/YHIGH
48 * IF((PLGTNR.EQ.2) YUPL=(RETMAX-RETMIN)/YHIGH
49 * IF((XUPL.EQ.0.0) XUPL=(MAGMAX-MAGMIN)/XWIDE
50 * IF((IGRAPH.EQ.0) GO TO 21
51 * IF((PHSMIN.EQ.0.0) PHSMIN=-360.0
52 * IF((PHSUPL.EQ.0.0) PHSUPL=45.0
53 * READ(5,9) SETALP,SETRET
54 * VINPNT(1)=1.0
55 * IF((NVINPT.EQ.0).OR.(PLGTNR.LE.2)) GO TO 22
56 * READ(5,9) (VINPNT(I),I=1,NVINPT)
57 * GO TO 23
58 * READ(5,9) (CURPAR(I),I=1,NPCURV)
59 * DO 24 JN=1,NPPI
60 * READ(5,9) (AN(JN,I),I=1,16)
61 * DO 26 JD=1,NCP1
62 * READ(5,9) (AD(JD,I),I=1,16)

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119 GO TO 121
120 XMAG(IN)=10.0*ALOG10(XMAG(IN))
    IF((XMAG(IN).LT.MAGMIN).OR.(XMAG(IN).GT.MAGMAX)) GO TO 121
    IP=IP+1
    X(IP)=(XMAG(IN)-MAGMIN)/XSCALE
    Y(IP)=(VAL-ZMIN)/YSCALE
    IF(ZSCALE.EQ.0) Y(IP)=(ALOG10(VAL)-ZLOGMN)/YSCALE
121 IN=IN+1
    IF(IN.GT.NRPTS) GO TO 141
    GO TO 81
122 IF(ZSCALE.EQ.0) GO TO 123
    OMEGA(IW)=ZMIN+(IW-1)*ZINC
    GO TO 124
123 TLZVAL=TLZMIN+(IW-1)*ZINC
    OMEGA(IW)=10.0*TLZVAL
124 SUMN=C.C
    DO 125 I=1,NAPI
    NWEXP=2*(I-1)
    SUMN=SUMN+CN(I)*OMEGA(IW)**NWEXP
    SUMC=C.C
    DO 126 J=1,NDPI
    NWEXP=2*(J-1)
    SUMD=SUMD+CD(J)*OMEGA(IW)**NWEXP
126 XMAG(IW)=ABS(SUMN/SUMD)
127 IF(IGAPH.EQ.1) GO TO 128
    PHAS1=C.0
    GO TO 133
128 PNEV=PAN(1)
    DO 129 I=3,NAPI,2
    PNEV=PNEV+PAN(I)*OMEGA(IW)**(I-1)*((-1)**((I-1)/2))
129 PNOD=C.0
    DO 130 I=2,NAPI,2
    PNOD=PNOD+PAN(I)*OMEGA(IW)**(I-1)*((-1)**((I/2+1))
130 PDEV=PAD(1)
    DO 131 I=3,NAPI,2
    PDEV=PDEV+PAD(I)*OMEGA(IW)**(I-1)*((-1)**((I-1)/2))
131 PNOD=C.C
    DO 132 I=2,NAPI,2
    PNOD=PNOD+PAD(I)*OMEGA(IW)**(I-1)*((-1)**((I/2+1))
132 PREAL=PNEV*PDEV+PNOD*PDOD
    PIMAG=PNOD*PDEV-PNEV*PDOD
    TVAL=PTMAG/PTVAL
    PHAS1=ATAN(TVAL)
    IF(PREAL.LT.0) PHAS1=-3.141593+PHAS1
    IF((PREAL.GT.0).AND.(PIMAG.GT.0)) PHAS1=-2.0*3.141593+PHAS1
    PHSDRG(IW)=(PHAS1*180.0)/3.141593
133 IF(NVINPT.GE.1) XMAG(IW)=XMAG(IW)*(VINOUT(KV)**2.0)
    IF(MAGSCL.EQ.0) GO TO 134

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TE11377
TE11378
TE11379
TE11380
TE11381
TE11382
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TE11386
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TE11390
TE11391
TE11392
TE11393
TE11394
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TE11396
TE11397
TE11398
TE11399
TE11400
TE11401
TE11402
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TE11408
TE11409
TE11410
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TE11423
TE11424

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134 IF(MAGSCL.EQ.2) GO TO 136
    XMAG(IW)=SQRT(XMAG(IW))
    GO TO 136
135 IF((XMAG(IW)-EPSLOG).GE.0.0) GO TO 135
    XMAG(IW)=-1.0E 70
    GO TO 140
136 XMAG(IW)=10.0*ALOG10(XMAG(IW))
    IF(PLCTNR.NE.5) GO TO 139
    XX=XMAG(IW)
    OMEGA=OMEGA(IW)
    CALL ARVAR (AL,BE,XX,CMG)
    IF (KNR.EQ.0) GO TO 137
    GO TO 91
137 ALPHA(IW)=AL
    BETA(IW)=BE
    KKI=1
138 IF((XMAG(IW).LT.MAGMIN).OR.(XMAG(IW).GT.MAGMAX)) GO TO 140
    IP=IP+1
    MAXIP(IC,IP)=IP
    PHASE(IC,IP)=PHSDEG(IW)
    X(IP)=(MAGMAX-XMAG(IW))/XSCALE
    YY(IC,IP)=(OMEGA(IW)-ZMIN)/YSCALE
    IF(OMGSCL.EQ.0) YY(IC,IP)=(ALOG10(OMEGA(IW))-ZLOGMN)/YSCALE
    Y(IP)=YY(IC,IP)
140 IW=IW+1
    IF(IW.GT.NRPNTS) GO TO 141
    IF(IW.NINPT.GE.1) GO TO 81
    GO TO 121
C***** WRITE CUT RESULTS *****
141 WRITE(6,1) EQ.0) GO TO 166
142 IF(IWRITE.EQ.0) IC
143 WRITE(6,143) IC
144 FORMAT(/,10X,'THE FOLLOWING POINTS WERE DETERMINED FOR CURVE NUMBE
    *R',I3,/)
145 FORMAT(10X,'POINT NR',5X,'ALPHA',7X,'BETA',6X,'MAGNITUDE',5X,'OMEG
    *A',/)
146 FORMAT(14X,I3,1X,1P4E12.3)
147 FORMAT(10X,'POINT NR',5X,'ALPHA',7X,'BETA',6X,'MAGNITUDE',5X,'OMEG
    *A',7X,'PHASE',6X,'VINUT',/)
148 FORMAT(14X,I3,1X,1P6E12.3)
149 GO TO (149,151,153,155,157),PLCTNR
150 WRITE(6,144)
    DO 150 KP=1,NRPNTS,IWRITE
    GO 150 KP=1,NRPNTS,IWRITE
151 WRITE(6,145) KP,ALPHA(KP),SETBET,XMAG(KP),CURPAR(ID)
152 DO 152 KP=1,NRPNTS,IWRITE
    WRITE(6,145) KP,SETALP,BETA(KP),XMAG(KP),CURPAR(ID)

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153 GO TO 162
154 WRITE(6,146) NRPNTS,IWRITE
155 DO 154 KP=1, NRPNTS,IWRITE
156 WRITE(6,147) KP,CURPAR(ID),SETPET,XMAG(KP),OMEGA(KP),PHSDEG(KP),VI
*NDUT(KV)
GO TO 159
157 WRITE(6,146) NRPNTS,IWRITE
158 DO 157 KP=1, NRPNTS,IWRITE
159 WRITE(6,147) KP,SETALP,CURPAR(ID),XMAG(KP),OMEGA(KP),PHSDEG(KP),VI
*NDUT(KV)
GO TO 161
160 WRITE(6,146) NRPNTS,IWRITE
161 DO 160 KP=1, NRPNTS,IWRITE
162 WRITE(6,147) KP,BETA(KP),XMAG(KP),OMEGA(KP),PHSDEG(KP),V
*INPLT(KV)
163 WRITE(6,160) 'THE ORIGIN OF THIS GRAPH HAS BEEN SHIFTED TO THE LOW
*ER RIGHT FOR STANDARD FORM.',//
*LOCKWISE EQ.1) WRITE(6,161)
164 FORMAT(10X,'THE PHASE PLOT MUST ALSO BE ROTATED 90 DEGREES CLOCKWI
*SE TO PUT IT IN THE STANDARD FORM.',//)
165 IF(IP.LT.2) GO TO 167
166 WRITE(6,163) IP
167 FORMAT(//,10X,'NUMBER OF POINTS PLOTTED (NUMBER WITHIN SPECIFIED RA
*NGE):',14)
GO TO 166
168 WRITE(6,165) IC
169 FORMAT(//,10X,'CURVE NUMBER',13,' WAS NOT PLOTTED DUE TO AN INSUFFI
*CIENT NUMBER OF ACCEPTABLE PCINTS.',//)
GO TO 167
C***** PLOT CURVE *****
166 IF(IGRAPH.EQ.-1) GO TO 167
CALL GRPLCY(2)
IP=0
IN=1
IW=1
167 IF(NVINPT.EQ.0) GO TO 168
KV=KV+1
IF(KV.GT.NVINPT) GO TO 168
GO TO 81
168 ID=ID+1
IF(ID.GT.NPCURV) GO TO 169
GO TO 81
169 IF(IGRAPH.EQ.-1) GO TO 175
CALL GRPLCY(3)
IF(IGRAPH.EQ.0) OR.(PLCTNR.LE.2) GO TO 175
C***** PLOT PHASE *****

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TE11473
TE11474
TE11475
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[illegible]



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16 CALL NUMBER (XZ,YZ,0.07,ZNUM,0.0,2)
C ***** LABEL HORIZONTAL AXIS *****
XZ=XWIDE/2.0-0.24
YZ=-0.25
LTR=4
IF(MSCALE.EQ.0) LTR=5
IF(MSCALE.EQ.6) LTR=6
CALL SYMBOL (XZ,YZ,0.14,ANAME(LTR),0.0,8)
IF(ZSCALE.EQ.0) GC TO 20
C ***** DRAW VERTICAL AXIS MARKERS *****
NRHLPI=(ZMAX-ZMIN)/YUPL+1
DO 18 LNR=1,NRHLPI
X(1)=0.0
X(2)=XWIDE
Y(1)=(LNR-1)*YINCR
Y(2)=Y(1)
CALL LINE (X,Y,2,1,1)
YNUM=ZMIN+(LNR-1)*YUPL
XZ=X(2)+0.05
YZ=Y(2)
18 CALL NUMBER (XZ,YZ,0.07,YNUM,0.0,2)
20 GO TO 22
22 INUM=1,NDECAD
DO 22 JNUM=1,10
YNUM=JNUM
X(1)=0.0
X(2)=XWIDE
Y(1)=(ALOG10(ZNUM)+INUM-1)/YSCALE
Y(2)=Y(1)
CALL LINE (X,Y,2,1,1)
IF(JNUM.GT.5) GC TO 22
LNUM=10.0*ZLCGMN+30.0+(INUM-1)*10.0+JNUM
XZ=X(2)+0.05
YZ=Y(2)
CALL SYMBOL (XZ,YZ,0.07,LGSCAL(LNUM),0.0,4)
22 CONTINUE
C ***** LABEL VERTICAL AXIS *****
24 XZ=XWIDE+0.47
YZ=YHIGH/2.0-0.36
LTR=3
IF(PLCTNR.LE.2) LTR=PLCTNR
CALL SYMBOL (XZ,YZ,0.14,ANAME(LTR),90.0,8)
GO TO 20
C ***** PLOT CURVES *****
20 7 IC=IC
XCNR=X(IP)+0.02
YCNR=Y(IP)-0.02
CALL LINE (X,Y,IP,1,1)

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CALL NUMBER (XCNR,YCNR,0.07,ZIC,0.0,-1)
GO TO SC ***** END GRAPH *****
C***** YUP=YHIGH+4.0 *****
LC CALL PLCT (0.0,YUP,-3) *****
SC RETURN *****
END *****

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SUBROUTINE INTTEN (AL,PE,W,X2)
  THIS SUBROUTINE IS CALLED BY THE ABVAR SUBROUTINE WHEN MDATA =1.
  IT IS NEEDED WHEN A PARAMETER IS A FUNCTION OF AN INTERNAL TRANSFER
  FUNCTION. THE SUBROUTINE COMPUTES THE MAGNITUDE OF THE INTERNAL
  TRANSFER FUNCTION AND RETURNS IT TO THE ABVAR SUBROUTINE AS X2. THE
  ADDITIONAL DATA CARDS REQUIRED ARE INDICATED BELOW.

  CARD FORMAT      SYMBOL
  17      8110      NRNUM2
                     NRDEN2
                     SYMRC1 USAGE
                     ORDER OF THE NUMERATOR POLYNOMIAL OF THE INTERNAL
                     TRANSFER FUNCTION. (MAX=10)
                     ORDER OF THE DENOMINATOR POLYNOMIAL OF THE
                     INTERNAL TRANSFER FUNCTION. (MAX=10)

  18      8E10.3      AN
                     NUMERATOR COEFFICIENTS IN ASCENDING ORDER OF THE S
                     EXPONENTS. TWO CARDS ARE USED FOR EACH OF THE S
                     EXPONENTS FROM S**0 THROUGH THE POLYNOMIAL ORDER.
                     (1)      *1.0,      *R**2,      *R**3,      *R**3,
                     *A,      *A**2,      *A**2,      *A**2,      *A**2,      *A**2,
                     *A**3,      *A**3,      *A**3,      *A**3,      *A**3,      *A**3,
                     (2)      *A**2,      *A**2,      *A**2,      *A**2,      *A**2,      *A**2,
                     *A**3,      *A**3,      *A**3,      *A**3,      *A**3,      *A**3,

  10      8E10.3      AD
                     DENOMINATOR COEFFICIENTS IN ASCENDING ORDER OF THE S
                     EXPONENTS. TWO CARDS ARE USED FOR EACH OF THE S
                     EXPONENTS FROM S**0 THROUGH THE POLYNOMIAL ORDER.
                     SAME FORMAT AS CARD NUMBER 18 (NUMERATOR COEFF).

  **** PROGRAM FOLLOWS ****
  DIMENSION AA(11,16),AD(11,16),AN(11,16)
  DIMENSION A(11),C(11),CD(11),CN(11)
  COMMON MAGSCL,MABVAR,EPSLOG,KNR,KK1,MDATA
  FORMAT(1H1)
  FORMAT(11O)
  FORMAT(11O,3)
  FORMAT(11O,3)
  FORMAT(11O,3)
  IF(MABVAR.GT.1) GO TO 91
  **** WRITE TRANSFER FUNCTION DECK ****

```

[illegible]



```

97 C(11)=A(11)*A(11)-2.0*A(9)*A(11)
98 C(10)=A(10)*A(10)+2.0*(A(7)*A(11)-A(8)*A(10))
99 C(9)=A(9)*A(9)+2.0*(A(5)*A(11)-A(5)*A(10)+A(7)*A(9))
100 C(8)=A(8)*A(8)-2.0*(A(5)*A(11)-A(4)*A(10)+A(5)*A(8))
101 C(7)=A(7)*A(7)+2.0*(A(3)*A(11)-A(4)*A(10)+A(3)*A(9))
102 C(6)=A(6)*A(6)-2.0*(A(1)*A(11)-A(2)*A(10)+A(3)*A(8)+A(5)*
    *A(7))
103 C(5)=A(5)*A(5)+2.0*(A(1)*A(3)-A(2)*A(8)+A(3)*A(4))
104 C(4)=A(4)*A(4)-2.0*(A(1)*A(7)-A(2)*A(5)+A(3)*A(5))
105 C(3)=A(3)*A(3)+2.0*(A(1)*A(1)-A(2)*A(4))
106 C(2)=A(2)*A(2)-2.0*A(1)*A(3)
107 C(1)=A(1)*A(1)
108 IF(IKCOUNT.EQ.2) GO TO 110
    DO 108 IG=1,N
    CN(IG)=C(IG)
    N=NDP1
    IKCOUNT=2
    DO 109 I=1,N
    DO 109 J=1,16
    AA(I,J)=AA(I,J)
    GO TO 103
109 DO 111 IG=1,N
110 CD(IG)=C(IG)
111 SUMN=0.0
112 DO 113 I=1,NDP1
    NWEXP=2*(I-1)
    SUMN=SUMN+CN(I)*W*WEXP
113 SUMC=0.0
    DO 114 J=1,NDP1
    NWEXP=2*(J-1)
    SUMD=SUMD+CD(J)*W*WEXP
114 X2=ARCS(SUMN/SUMD)
    IF(MAGSCL.EQ.2) GO TO 120
    IF(MAGSCL.EQ.0) GO TO 116
    X2=SQRT(X2)
    GO TO 120
116 IF((X2-EPSSLOG).GE.0.0) GO TO 110
    X2=-1000.0
    GO TO 120
118 X2=10.0*ALCG10(X2)
120 RETURN
    END

```

SUBROUTINE ARVAR (AL,BF,XX,CWG)

THIS SUBROUTINE IS USED TO DESCRIBE THE NONLINEAR PARAMETER CHARACTERISTICS WHEN PLOTNP=5. ADD THE NECESSARY FORTRAN STATEMENTS



```

C      TO REFLECT THE DESIRED RELATIONSHIPS (X=MAGNITUDE IN MAGSCL UNITS).
C
COMMON MAGSCL,MABVAR,EPSLOG,KNR,KK1,MDATA
A=AL
B=BE
X=XX
W=CMG
EPSA=1.0E-04
EPSB=1.0E-04
ANEW=A
RNEW=R
IF(MDATA.NE.1) GC TO 10
CALL INTFN (AL,BE,W,X2)
CONTINUE
ADEL=ABS(ANEW-A)
RDEL=ABS(RNEW-R)
KNR=0
IF((ADEL.GE.EPSA).OR.(BDEL.GE.EPSB)) KNR=1
AL=ANEW
BE=RNEW
KK1=KK1+1
20 RETURN
10

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TF1803
TF1904
TF1805
TF1806
TF1807
TF1808
TF1809
TF1810
TF1811
TF1812
TF1813
TF1814
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TF1816
TF1817
TF1818
TF1819
TF1820
TF1821
TF1822
TF1823
TF1824
TF1825

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[illegible][illegible]

SYMBOL USAGE

```

PLOT NUMBER (Y-AXIS VS X-AXIS)
11=ALPHA VS OMEGA, BETA FIXED, MAGNITUDE PARAMETER
12=BETA VS OMEGA, ALPHA FIXED, MAGNITUDE PARAMETER
13=ALPHA VS BETA, OMEGA FIXED, MAGNITUDE PARAMETER
14=ALPHA VS BETA, MAGNITUDE FIXED, OMEGA PARAMETER
ORDER OF DENOMINATOR POLYNOMIAL (MAX=10).
ORDER OF PARAMETER VALUES (1-16). AND MINVALUES.
NUMBER OF COMPUTATIONS BETWEEN PLOTTED PER CURVE
IT EQUALS THE NUMBER OF POINTS
(1-900). IF SET=0, NRPOINTS=000.
NUMBER OF COMPUTATIONS BETWEEN PRINTOUTS (1-900).
IF SET=0, NO COMPUTATION RESULTS ARE PRINTED.

```

```

GRAPH CRDER. DESIRED.
-- 1= NO GRAPHS DESIRED.
  0= GRAPHS ARE DESIRED.
ALPHA OUTPUT AXIS SCALE CODE. USED WITH PLOTNP 1,
3,4.
0=LOG SCALE.
1=LINEAR SCALE.
ALPHA OUTPUT AXIS SCALE CODE. USED WITH PLOTNR 2,
3,4.
0=LOG SCALE.
1=LINEAR SCALE.
MAGNITUDE PARAMETER SCALE CODE.
0=DR VALUES.

```

99













```

45 ID=1
46 DO 47 L=1,5
47 XRO(L)=C.C050010
  XIO(L)=C.C100010
  IW=1
  IP=1
  WRITE(6,1)
  WRITE(6,48) ID
48 *  FORMAT(/,IX,'THE FOLLOWING POINTS WERE DETERMINED FOR CURVE NR',I3
    IF(PLCTNR-2) 49,51,53
49 *  WRITE(6,50)
50 *  FORMAT(IX,'PCINT NR',6X,'BETA',5X,'MAGNITUDE',5X,'OMEGA',7X,'ALPHA
    (ROOT OF PCYNOMIAL-IMAG PART LISTED UNDER REAL PART)')
  GO TO 55
51 *  WRITE(6,52)
52 *  FORMAT(IX,'PCINT NR',5X,'ALPHA',5X,'MAGNITUDE',5X,'OMEGA',7X,'BETA
    (ROOT OF PCYNOMIAL-IMAG PART LISTED UNDER REAL PART)')
  GO TO 55
53 *  WRITE(6,54)
54 *  FORMAT(IX,'PCINT NR',5X,'OMEGA',5X,'MAGNITUDE',5X,'BETA',9X,'ALPHA
    (ROOT OF PCYNOMIAL-IMAG PART LISTED UNDER REAL PART)')
55 *  IF(ID.EQ.1) GO TO 56
56 *  GO TO (73,73,58,58), PLCTNR
57 *  BE=SETREF
  SETVAL=RE
  GO TO 63
58 *  RINC=(BETMAX-BETMIN)/NRPTM1
  RINC=(BETMAX-BETMIN)/NRPTM1
  IF(BETSCL.EQ.0) RINC=(ALOG10(BETMAX)-ALOG10(BETMIN))/NRPTM1
  IF(PLCTNR.EQ.4) GO TO 59
  W=SETLONG
  SETVAL=WP
  XMA=CUPPAR(ID)
  IF(MAGSCL.EQ.1) XMA=XMA**2
  IF(MAGSCL.EQ.0) XMA=10.0**(XMA/10.0)
  GO TO 60
59 *  XMA=SETMAG
  IF(MAGSCL.EQ.1) XMA=XMA**2
  IF(MAGSCL.EQ.0) XMA=10.0**(XMA/10.0)
  SETVAL=XMA
  W=CUPPAR(ID)
  IF(BETSCL.EQ.0) GO TO 61
  BE=BETMIN+(IW-1)*BINC
  GO TO 62
61 *  BEL=ALOG10(BETMIN)+(IW-1)*BINC
  BE=10.0**REL
  XH=RE
62

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TF222233
TF222234
TF222235
TF222236
TF222237
TF222238
TF222239
TF222240
TF222241
TF222242
TF222243
TF222244
TF222245
TF222246
TF222247
TF222248
TF222249
TF222250
TF222251
TF222252
TF222253
TF222254
TF222255
TF222256
TF222257
TF222258
TF222259
TF222260
TF222261
TF222262
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TF222278
TF222279
TF222280

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75 IF(OMGSCL.EQ.0) WINC=(ALCG10(OMGMAX)-ALCG10(OMGMIN))/NRPTM1
   IF(OMGSCL.EQ.0) GO TO 76
   W=OMGMIN+(IW-1)*WINC
   GO TO 77
76 WL=ALCG10(OMGMIN)+(IW-1)*WINC
   W=10.0**WL
77 XH=W
C***** SET UP POLYNOMIAL AND SOLVE FOR ROOTS *****
78 DO 79 I=1,2
   DO 79 J=1,NDP1
   DO 79 JJ=J,NDP1,2
   XE=(J-1)+(JJ-1)
   DO 79 K=1,7
   XMP(I,J,JJ,K)=(W**XE)*XM(I,J,JJ,K)
79 IF(XMA.EQ.1.0) XMA=0.99
80 DO 81 K=1,7
   XN(K)=0.0
   DO 81 J=1,NDP1
   DO 81 JJ=J,NDP1,2
   XN(K)=XMP(I,J,JJ,K)-XMA*XMP(2,J,JJ,K)+XN(K)
81 DO 82 I=1,7
   IF(ABS(XN(I)).LT.1.0E-20) XN(I)=0.0
82 KPDIM=7
   IF(XN(KPDIM).NE.0.0) GO TO 84
83 KPDIM=KPDIM-1
   GO TO 83
84 KPCRD=KPDIM-1
   DO 85 L=1,6
   XR(L)=0.0
85 XI(L)=0.0
   GO TO 86
86 XR(1)=-XN(1)/XN(2)
   GO TO 87
87 CALL PCLRT2(XN,XR,XI)
   GO TO 81
88 CALL POLRT3(XN,COF,KPCRD,XR,XI,XRO,XIO,IER)
   IF(IER.EQ.0) GO TO 89
   WRITE(6,3) IO,IW,IER
89 DO 90 L=1,KPCRD
   XRO(L)=-XI(L)/10.0
   XIO(L)=-XP(L)/10.0
90 DO 92 I=1,KPCRD
   IF(ABS(XR(I)).LE.1.0E-50) XR(I)=0.0
92 IF(ABS(XI(I)).LE.1.0E-50) XI(I)=0.0
93 IF(IW.EQ.1) GO TO 96
   IWK=IW-1
   IF(IWK-IWRITE) 101,96,95
94 IF(IWK-IWRITE

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```

96 GO TO 94
97 IF (KPDIM.EQ.1) GO TO 99
98 WRITE(6,97) IW,SETVAL,CURPAR(10),XH,(XR(K),K=1,KP73D)
99 FORMAT(4X,I3,1P9F12.3)
100 WRITE(6,98) (XI(K),K=1,KPORD)
101 FORMAT(4X,1P6F12.3)
102 GO TO 110
103 WRITE(6,100) IW,XN(1)
104 FORMAT(/,10X,'ITERATION',I4,' RESULTED IN A DEGENERATE POLYNOMIAL
105 *CE CRDER ZERC. CCNSTANT=',1P1E12.3,/)
106 GO TO 110
107 ***** ABSTRACT USEABLE ROOTS *****
108 IPK=0
109 DO 102 K=1,KPCRD
110 IF (XI(K).NE.C.O) GC TO 102
111 IF ((XR(K).LT.PARMIN).OR.(XR(K).GT.PARMAX)) GO TO 102
112 IPK=1
113 CONTINUE
114 IF (IPK.EQ.0) GO TO 110
115 DO 103 K=1,KPCRD
116 IF (XI(K).NE.C.O) GC TO 102
117 IF ((XR(K).LT.PARMIN).OR.(XR(K).GT.PARMAX)) XR(K)=1.0F50
118 K=1
119 IF (XR(K+1).GE.XP(K)) GC TO 106
120 XX=XR(K)
121 XR(K)=XR(K+1)
122 XR(K+1)=XX
123 GO TO 104
124 K=K+1
125 IF (K.EQ.KPCRD) GC TO 107
126 GO TO 105
127 DO 109 K=1,KPCRD
128 YP(IP,K)=XR(K)
129 IF (PLCTNR.GT.2) GO TO 108
130 XP(IP,K)=K
131 GO TO 109
132 XP(IP,K)=PE
133 CONTINUE
134 IP=IP+1
135 IW=IW+1
136 IF (IW.GT.NRPNTS) GC TO 111
137 GO TO (75,75,60,60), PLCTNR
138 ***** GRAPH *****
139 IPM1=IP-1
140 WRITE(6,112) IPM1,ID
141 FORMAT(10X,I4,' ACCEPTABLE POINTS WERE FOUND FOR CURVE NUMBER',I3,
142 *)
143 IF (IGRAPH.EQ.-1) GC TO 115
144 IF (IPM1.GE.2) GO TO 115

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113 WRITE(6,114) ID
114 FORMAT(10X,'CURVE NUMBER',I3,' WAS NOT PLOTTED SINCE LESS THAN 2 A
      *ACCEPTABLE PCINTS WERE FOUND.',/)
115 IF(ZSCALE.EQ.0) GO TO 117
116 DO 116 IP=1,IPM1
117 Y(IP)=(YP(IP,1)-ZMIN)/YSCALE
118 GO TO 119
119 DO 118 IP=1,IPM1
120 Y(IP)=(ALCGIO(YP(IP,1))-YLCGMN)/YSCALE
121 GO TO 123
122 X(IP)=(XP(IP,1)-XMIN)/XSCALE
123 NRPP=IPM1
124 I7=2
125 IZNR=C
126 YVALMX=1.0E5C
127 DO 125 IP=1,IPM1
128 IF(YP(IP,IZ)) LT YVALMX) IZNR=1
129 IF(I7NR.EQ.0) GO TO 130
130 DO 128 IP=1,IPM1
131 IZP=I7
132 IF(YP(IP,IZP).GE.YVALMX) GO TO 127
133 X(IQ)=X(IP)
134 Y(IQ)=(YP(IP,IZP)-ZMIN)/YSCALE
135 IF(ZSCALE.EQ.0) Y(IQ)=(ALCGIO(YP(IP,IZP))-YLCGMN)/YSCALE
136 GO TO 128
137 IZP=IZP-1
138 IF(IZP.EQ.0) GO TO 128
139 GO TO 127
140 IQ=IQ+1
141 NRPP=IQ-1
142 CALL GRPLOT(2)
143 IZ=I7+1
144 IF(IZ.EQ.KPDIM) GO TO 130
145 GO TO 124
146 ID=ID+1
147 IF(ID.GT.NPCURV) GO TO 131
148 GO TO 146
149 IF(IGRAPH.EQ.-1) GO TO 132
150 CALL GRPLOT(3)
151 IRUN=IRUN+1
152 IF(IPUN.GT.NRUN) GO TO 900

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          GO TO 11
          900 CONTINUE
          STOP
          END
TE2472
TE2474
TE2475
TE2476

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C
C
C
C
      SUBROUTINE GRPLOT(K)
C
C      THIS SUBROUTINE PROVIDES THE PLOTTING PACKAGE FOR THE PROGRAM. THE
C      THE SUBROUTINES CALLED ARE EXPLAINED IN U.S.N. POSTGRADUATE SCHOOL
C      COMPUTER FACILITY TECHNICAL NOTE NO. 0211-03.
C
      INTEGER PLCTNR, ZSCALE
      REAL LGSCAL(70)/4H.001,4H.002,4H.003,4H.004,4H.005,4H.006,4H.007,
      *4H.008,4H.009,4H.01,4H.011,4H.012,4H.013,4H.014,4H.015,4H.016,
      *4H.017,4H.018,4H.019,4H.02,4H.021,4H.022,4H.023,4H.024,4H.025,
      *4H.026,4H.027,4H.028,4H.029,4H.03,4H.031,4H.032,4H.033,4H.034,4H.035,
      *4H.036,4H.037,4H.038,4H.039,4H.04,4H.041,4H.042,4H.043,4H.044,4H.045,
      *4H.046,4H.047,4H.048,4H.049,4H.05,4H.051,4H.052,4H.053,4H.054,4H.055,
      *4H.056,4H.057,4H.058,4H.059,4H.06,4H.061,4H.062,4H.063,4H.064,4H.065,
      *4H.066,4H.067,4H.068,4H.069,4H.07,4H.071,4H.072,4H.073,4H.074,4H.075,
      *4H.076,4H.077,4H.078,4H.079,4H.08,4H.081,4H.082,4H.083,4H.084,4H.085,
      *4H.086,4H.087,4H.088,4H.089,4H.09,4H.091,4H.092,4H.093,4H.094,4H.095,
      *4H.096,4H.097,4H.098,4H.099,4H.1,4H.101,4H.102,4H.103,4H.104,4H.105,
      *4H.106,4H.107,4H.108,4H.109,4H.11,4H.111,4H.112,4H.113,4H.114,4H.115,
      *4H.116,4H.117,4H.118,4H.119,4H.12,4H.121,4H.122,4H.123,4H.124,4H.125,
      *4H.126,4H.127,4H.128,4H.129,4H.13,4H.131,4H.132,4H.133,4H.134,4H.135,
      *4H.136,4H.137,4H.138,4H.139,4H.14,4H.141,4H.142,4H.143,4H.144,4H.145,
      *4H.146,4H.147,4H.148,4H.149,4H.15,4H.151,4H.152,4H.153,4H.154,4H.155,
      *4H.156,4H.157,4H.158,4H.159,4H.16,4H.161,4H.162,4H.163,4H.164,4H.165,
      *4H.166,4H.167,4H.168,4H.169,4H.17,4H.171,4H.172,4H.173,4H.174,4H.175,
      *4H.176,4H.177,4H.178,4H.179,4H.18,4H.181,4H.182,4H.183,4H.184,4H.185,
      *4H.186,4H.187,4H.188,4H.189,4H.19,4H.191,4H.192,4H.193,4H.194,4H.195,
      *4H.196,4H.197,4H.198,4H.199,4H.2,4H.201,4H.202,4H.203,4H.204,4H.205,
      *4H.206,4H.207,4H.208,4H.209,4H.21,4H.211,4H.212,4H.213,4H.214,4H.215,
      *4H.216,4H.217,4H.218,4H.219,4H.22,4H.221,4H.222,4H.223,4H.224,4H.225,
      *4H.226,4H.227,4H.228,4H.229,4H.23,4H.231,4H.232,4H.233,4H.234,4H.235,
      *4H.236,4H.237,4H.238,4H.239,4H.24,4H.241,4H.242,4H.243,4H.244,4H.245,
      *4H.246,4H.247,4H.248,4H.249,4H.25,4H.251,4H.252,4H.253,4H.254,4H.255,
      *4H.256,4H.257,4H.258,4H.259,4H.26,4H.261,4H.262,4H.263,4H.264,4H.265,
      *4H.266,4H.267,4H.268,4H.269,4H.27,4H.271,4H.272,4H.273,4H.274,4H.275,
      *4H.276,4H.277,4H.278,4H.279,4H.28,4H.281,4H.282,4H.283,4H.284,4H.285,
      *4H.286,4H.287,4H.288,4H.289,4H.29,4H.291,4H.292,4H.293,4H.294,4H.295,
      *4H.296,4H.297,4H.298,4H.299,4H.3,4H.301,4H.302,4H.303,4H.304,4H.305,
      *4H.306,4H.307,4H.308,4H.309,4H.31,4H.311,4H.312,4H.313,4H.314,4H.315,
      *4H.316,4H.317,4H.318,4H.319,4H.32,4H.321,4H.322,4H.323,4H.324,4H.325,
      *4H.326,4H.327,4H.328,4H.329,4H.33,4H.331,4H.332,4H.333,4H.334,4H.335,
      *4H.336,4H.337,4H.338,4H.339,4H.34,4H.341,4H.342,4H.343,4H.344,4H.345,
      *4H.346,4H.347,4H.348,4H.349,4H.35,4H.351,4H.352,4H.353,4H.354,4H.355,
      *4H.356,4H.357,4H.358,4H.359,4H.36,4H.361,4H.362,4H.363,4H.364,4H.365,
      *4H.366,4H.367,4H.368,4H.369,4H.37,4H.371,4H.372,4H.373,4H.374,4H.375,
      *4H.376,4H.377,4H.378,4H.379,4H.38,4H.381,4H.382,4H.383,4H.384,4H.385,
      *4H.386,4H.387,4H.388,4H.389,4H.39,4H.391,4H.392,4H.393,4H.394,4H.395,
      *4H.396,4H.397,4H.398,4H.399,4H.4,4H.401,4H.402,4H.403,4H.404,4H.405,
      *4H.406,4H.407,4H.408,4H.409,4H.41,4H.411,4H.412,4H.413,4H.414,4H.415,
      *4H.416,4H.417,4H.418,4H.419,4H.42,4H.421,4H.422,4H.423,4H.424,4H.425,
      *4H.426,4H.427,4H.428,4H.429,4H.43,4H.431,4H.432,4H.433,4H.434,4H.435,
      *4H.436,4H.437,4H.438,4H.439,4H.44,4H.441,4H.442,4H.443,4H.444,4H.445,
      *4H.446,4H.447,4H.448,4H.449,4H.45,4H.451,4H.452,4H.453,4H.454,4H.455,
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      *4H.466,4H.467,4H.468,4H.469,4H.47,4H.471,4H.472,4H.473,4H.474,4H.475,
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IF(ZMAX.GT.0.1) ZLOGMX=0.0
IF(ZMAX.GT.1.0) ZLOGMX=1.0
IF(ZMAX.GT.10.0) ZLOGMX=2.0
IF(ZMAX.GT.100.0) ZLOGMX=3.0
IF(ZMAX.GT.1000.0) ZLOGMX=4.0
ADECAD=7LOGMX-ZLOGMN
IF(ILEG.EQ.0) GC TC 17
NDECAD=ADECAD
YLOGMN=ZLOGMX/YHIGH
YSCALE=ADECAD/EQ.0) GO TO 16
IF(NSCALE=(XMAX-XMIN)/XWIDE
XINCR=XUPL/XSCALE
C***** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** **
NRVLP1=(XMAX-XMIN)/XUPL+1
DO 15 LNR=1,ARVLP1
X(1)=(LNR-1)*XINCR
X(2)=X(1)
Y(1)=YHIGH
Y(2)=0.0
CALL LINE (X,Y,2,1,1)
ZNUM=XMAX-(LNR-1)*XUPL
IF(PLCTNR.LE.2) ZNUM=XMIN+(LNR-1)*XUPL
XZ=X(1)-0.14
YZ=-0.11
CALL NUMBER (XZ,YZ,0.07,ZNUM,0.0,2)
GO TO 15
15 ILOG=0
16 ZMIN=ZMIN
ZMAX=XMAX
GO MDECAD=ADECAD/XWIDE
XSCALE=ADECAD
ZMIN=ZMIN
DO 18 JNUM=1,MDECAD
DO 18 JNUM=1,10
ZNUM=JNUM
X(1)=(ALOG10(ZNUM)+INUM-1)/XSCALE
X(2)=X(1)
Y(1)=0.0
Y(2)=YHIGH
CALL LINE (X,Y,2,1,1)
IF(JNUM.NE.1) GO TC 18
LNUM=10.0*7LOGMN+30.0+(INUM-1)*10.0+JNUM
XZ=X(2)-0.14
YZ=-0.11
CALL SYMBOL (XZ,YZ,0.07,LGSCAL(LNUM),0.0,4)

```

```

18 CONTINUE
C***** LABEL HORIZONTAL AXIS *****
19 XZ=XWIDE/2.0-0.24
   YZ=-C.24
   LTR=3
   IF(PLCTNR.GT.2) LTR=2
   CALL SYMROL (XZ,YZ,0.14,ANAME(LTR),0.0,8)
C***** DRAW VERTICAL AXIS MARKERS *****
   IF(7.SCALE.EQ.0) GO TO 21
   NRHLP1=(ZMAX-ZMIN)/YUPL+1
   DO 20 LNR=1,NRHLP1
     X(1)=C.C
     X(2)=XWIDE
     Y(1)=(LNR-1)*YINCR
     Y(2)=Y(1)
     CALL LINE (X,Y,2,1,1)
     YNUM=7MIN+(LNR-1)*YUPL
     XZ=X(2)+C.C5
     YZ=Y(2)
20 CALL NUMBER (XZ,YZ,0.07,YNUM,0.0,2)
   GO TO 24
21 DO 22 INUM=1,NDECAD
   DO 22 JNUM=1,10
     ZNUM=JNUM
     X(1)=C.C
     X(2)=XWIDE
     Y(1)=(ALGO10(ZNUM)+INUM-1)/YSCALE
     Y(2)=Y(1)
     CALL LINE (X,Y,2,1,1)
     IF(JNUM.GT.5) GO TO 22
     LNUM=1C.0*YLCGMN+30.0+(INUM-1)*10.0+JNUM
     XZ=X(2)+C.C5
     YZ=Y(2)
     CALL SYMROL (XZ,YZ,0.07,LGSCAL(LNUM),0.0,4)
22 CONTINUE
C***** LABEL VERTICAL AXIS *****
24 XZ=XWIDE+0.47
   YZ=YHIGH/2.0-0.36
   LTR=1
   IF(PLCTNR.EQ.2) LTR=2
   CALL SYMROL (XZ,YZ,0.14,ANAME(LTR),0.0,8)
   GO TO 20
C***** PLOT CURVES *****
20 ZIC=1
   XCNR=X(NRPP)+0.02
   YCNR=Y(NRPP)-0.02
   CALL LINE (X,Y,NRPP,1,1)
   CALL NUMBER (XCNR,YCNR,0.07,ZIC,0.0,-1)

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C***** GO TO 5C *****
4C YUP=YHIGH+4.0 *****
CALL PLCT (0.0,YUP,-3) *****
CALL PLCT *****
5C RETURN *****
END *****

```

```

C
C SUBROUTINE PCLRT2(XN,XR,XI)
C THIS SUBROUTINE IS USED TO SOLVE FOR THE ROOTS WHEN THE POLYNOMIAL
C IS OF SECOND ORDER.

```

```

SUBROUTINE PCLPT3(XCCF,CCF,M,ROCTR,ROOT1,XR0,XIO,IER)
THIS SUBROUTINE IS USED TO SOLVE FOR THE ROOTS WHEN THE POLYNOMIAL
IS OF ORDER THREE OR GREATER.
      DIMENSION XCCF(1),CCF(1),RCOTR(1),ROOT1(1),XR0(1),XIO(1)
      DOUBLE PRECISION XO,YC,X,Y,XPR,YPR,UX,UY,V,YT,XT,U,XT2,YT2,SUMSO,
      *DX,DY,TEMP,ALPHA

```





```

55      GO TO 59
      IF IT=1
      XPR=X
      YPR=Y
C***** EVALUATE POLYNOMIAL AND DERIVATIVES *****
59      ICY=0
60      UX=0.0
      UY=0.0
      V=0.0
      YT=0.0
      XT=1.0
      U=COF(A+1)
      IF(U) 65,130,65
65      DO 70 I=1,N
      L=N-I+1
      TEMP=CCF(L)
      XT2=X*XT-Y*YT
      YT2=X*YT+Y*XT
      U=U+TEMP*XT2
      V=V+TEMP*YT2
      FI=1
      UX=UX+FI*XT*TEMP
      UY=UY-FI*YT*TEMP
      XT=XT2
      YT=YT2
70      SUMSQ=UX*UX+UY*UY
      IF(SUMSQ) 75,110,75
75      DX=(V*UY-U*UX)/SUMSQ
      X=X+DX
      DY=-(U*LY+V*UX)/SUMSQ
      Y=Y+DY
78      IF(DABS(DY)+DABS(DX)-1.0D-05) 100,51,51
100      DO 105 L=1,NXX
      MT=KJ1-L+1
      TEMP=XCOF(MT)
      XCOF(MT)=COF(L)
      COF(L)=TEMP
105      ITEMP=N
      NX=ITEMP
      NX=ITEMP
      IF(IFIT) 120,55,120
      IF(IFIT) 115,50,115
110      X=XPR
115      Y=YPR
      IF IT=C
120      IF(DABS(Y)-1.0D-4*DABS(X)) 135,125,125
122      ALPHA=X+X
125      SUMSQ=X*X+Y*Y

```

```

130      N=N-2      140
      GO TO 140
      X=0.0
      NX=NXX-1
      NXX=NXX-1
      Y=C.0
      SUMSQ=C.0
      ALPHA=X
      N=N-1
      COF(2)=COF(2)+ALPHA*COF(1)
      DO 150 L=2,N
      COF(L+1)=COF(L)+ALPHA*COF(L)-SUMSQ*COF(L-1)
      ROOT1(N2)=Y
      ROOTR(N2)=X
      N2=N2+1
      IF(SUMSQ) 160,165,160
      Y=-Y
      SUMSQ=C.0
      GO TO 155
      IF(N) 20,20,45
      RETURN
      END

```

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COMPUTER GRAPHICS





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